# Guidelines on flowpath characterization, dynamics and GW renewal

## Deliverable D2.2, Annexes, Genesis examples

## I. Zagreb example (UNIZG-RGNF): Artificial tracer experiment in unconfined heterogeneous alluvial aquifer with highly transient flow conditions

## Contents

# 1. Introduction

Artificial tracer experiment was carried out in order to determine transport parameters of the unconfined heterogeneous alluvial aquifer, namely longitudinal and transversal dispersivities as well as effective (seepage) velocity. Obtained parameters are planned to be used in prediction models for contaminant transport in Zagreb aquifer.

## 1.1. Site description

### 1.1.1. Location

Stara Loza site is a wellfield which was previously used for public water supply of the City of Zagreb, Croatia's capital (Fig. 1). Since 1997 the wellfield is out of operation. It has 5 pumping wells distanced app. 500 to 1000 m from the Sava River. 15 head observation wells (11 operating) and 7 concentration observation wells (4 operating) are concentrated in surrounding area and are still in use for monitoring of ground water levels and quality.

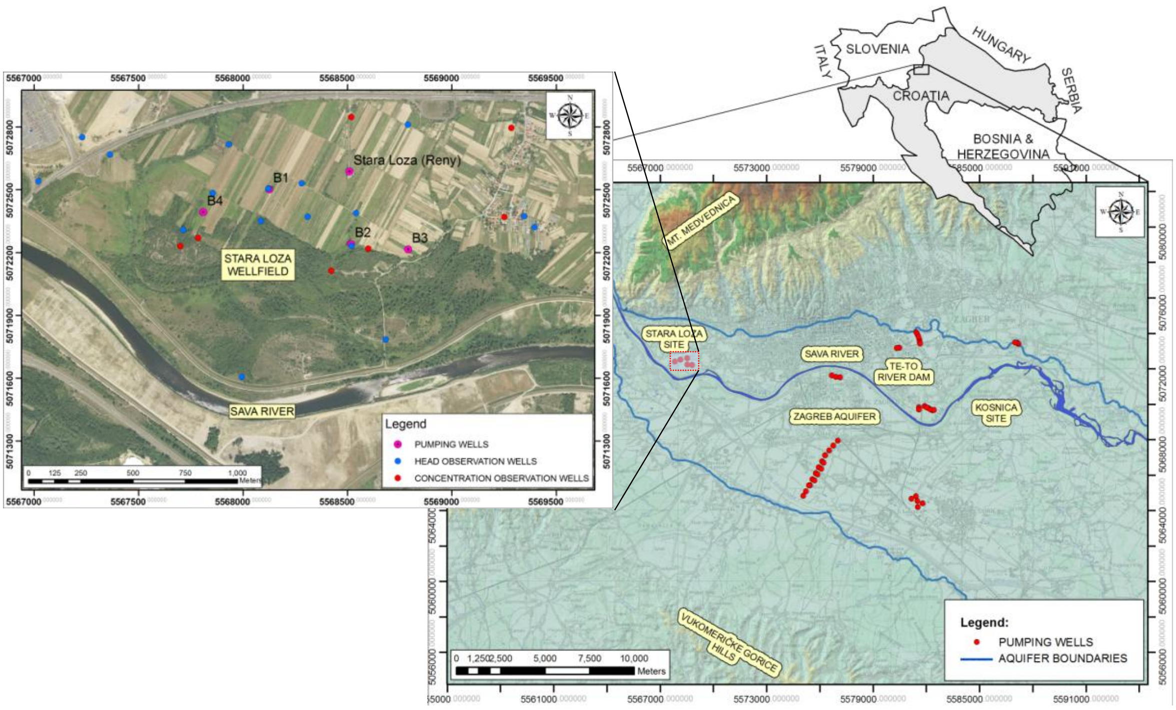


Figure 1 Stara Loza site

### 1.1.2. Geology

The Zagreb aquifer system is built of two Quaternary aquifers (Fig. 2), deeper Middle and Upper Pleistocene aquifer built of gravel, sand and clay in frequent lateral and vertical alterations (lacustrine-marshy deposits) and shallow Holocene unconfined alluvial aquifer built of medium-grain gravel mixed with sands (alluvial deposits) (Velić & Durn, 1993). Aquifer overburden is built of clay and silt and is mainly not present while the underlying bedrock is built of clay. At the Stara Loza site, overburden and lacustrine-marshy deposits are of insignificant thickness and aquifer is mainly represented with alluvial gravel and sand deposits with thickness ranging from 7 to 10 m.

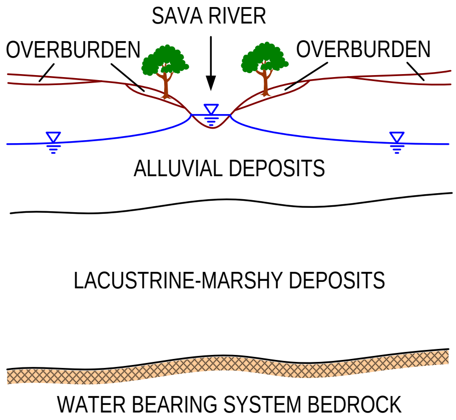


Figure 2 Schematic geological cross-section of the Zagreb aquifer system

### 1.1.3. Hydrogeology

Holocene alluvial aquifer, which is in focus of this research, is unconfined aquifer with water table connected to the Sava River. The Sava River, which is the main source of ground water recharge, is in continuous hydraulic connection with the shallow unconfined aquifer. Generally, late springs and summers are periods with low ground water levels while late autumns and early springs are periods with high ground water levels. Depending on the part of the year, the saturated thickness of the aquifer on the site ranges from 2.5 to 5 m. Hydraulic conductivity values on the site are 1500 m/day in average while hydraulic gradient values range from $5\times10^{-4}$ to $1\times10^{-3}$. Ground water velocities obtained from existing calibrated and validated numerical model of the Zagreb aquifer range from 3 to 7 m/day on the Stara Loza site. Due to high hydraulic conductivities of the aquifer and its hydraulic connection to the Sava River, the flow is highly transient and is governed by the Sava River elevations. Head contour map analysis (Posavec, 2006) showed that during high Sava River elevations, the river recharges ground water on all parts of the course while during medium and low river elevations; the river drains ground water on some parts of the course. The flow direction on the site changes from SW-NE during high Sava River elevations to NW-SE during low Sava River elevations. Spatial zonation of areas with higher impact of the Sava River on ground water levels was analyzed using recession curve models. The analysis of ground water level time series was performed using Master

Recession Curve (MRC) Tool (Posavec et al., 2006). Analysis of the spatial distribution of the obtained MRC's showed that the logarithmic regression prevails in parts of the aquifer near the Sava River while polynomial regression prevails in other parts of the aquifer (Figure 3). These results are logical and reasonable with respect to oscillations in ground water levels which occur faster in the vicinity of the Sava River. In other parts of the aquifer where such strong boundaries do not exist, ground water level oscillations occur less rapidly. The Stara Loza site, as presented on Fig. 3, belongs to the logarithmic regression model zone where higher impact of the Sava River elevations on ground water levels exist, therefore causing rapid changes in ground water flow direction i.e. highly transient flow conditions.

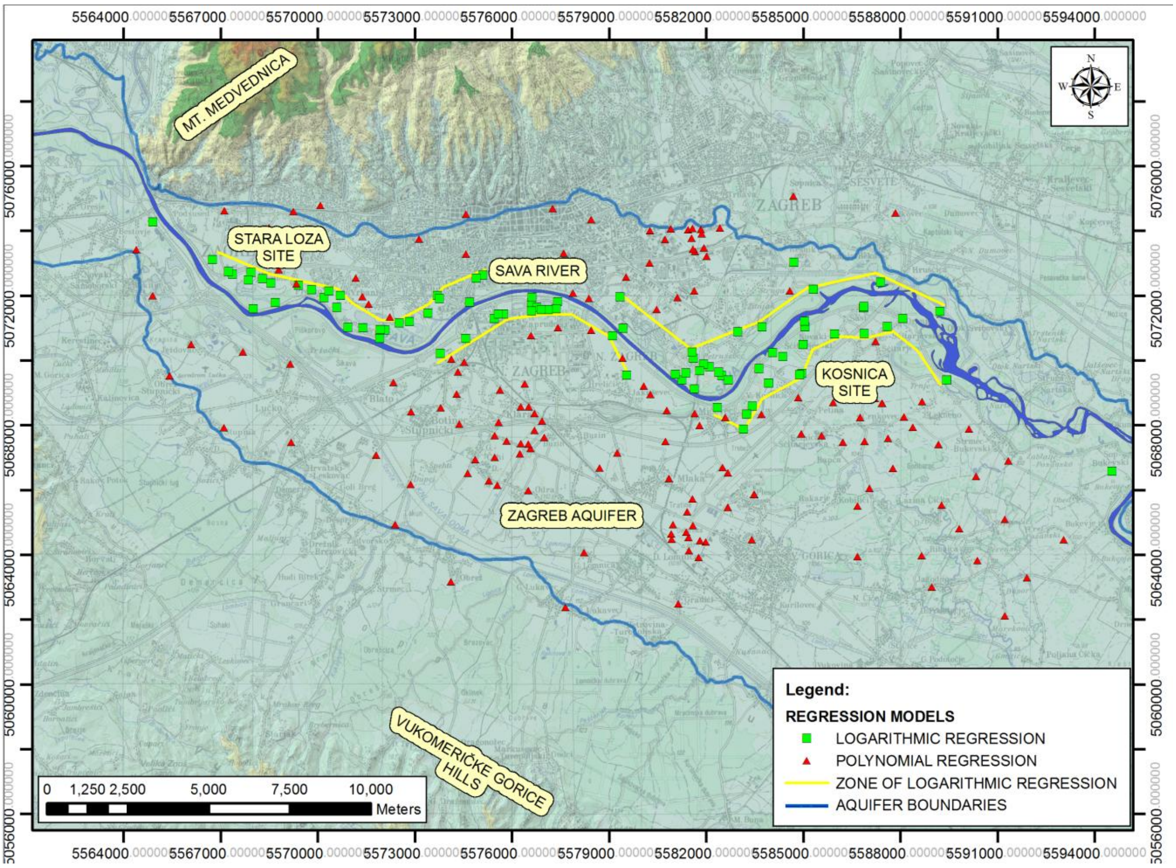

Figure 3 Regression models showing zones of higher impact of the Sava River

## 2. Artificial tracer experiment

### 2.1. Tracer experiment design

Tracer experiment is designed as a natural gradient tracer test with one (1) injection well and fourteen (14) observation wells (OW). The wells are 0.075 m in diameter and 10 m deep, with a 5 m screen above the wells bottom. Observation wells are placed in two rows, the first row containing seven (7) observation wells distanced 25.0 m from injection well, and the second row containing remaining seven (7) observation wells distanced 50.0 m from the injection well (Fig. 4). Due to highly transient flow conditions and rapid changes in ground water flow direction, experiment was planned to be completed within one month in order to avoid potential significant changes of ground water flow direction and deviation of tracer mass to areas without any observation wells installed. To achieve this, the distance between injection and observation wells needed to be less than 100 m, since ground water velocities obtained from existing numerical model of the Zagreb aquifer ranged from 3 to 7 m/day on the site. Preferably, even smaller distances between injection and observation well should be set in such conditions in order to diminish the effect of possible changes in ground water flow direction as much as possible and increase the probability of experiment success. Therefore, the distance between injection well and the first and second row of observation wells was set to 25.0 and 50.0 m, respectively.

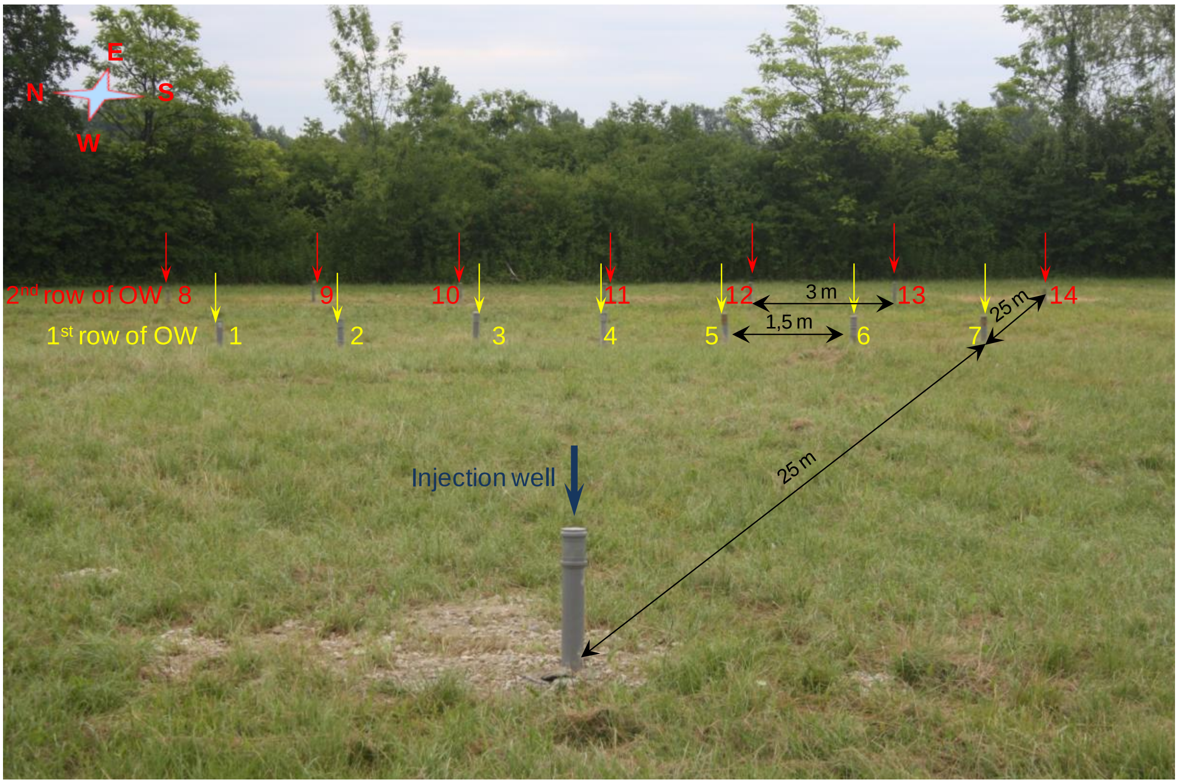


Figure 4 Injection well and observation wells setup

Due to expected transversal dispersivities of 0.25 to 1.25 m and associated transversal spread of 7.0 to 15.0 m for the first row and 10.0 to 22.0 m for the second row of observation wells, the distance between observation wells in the first and second row was set to 1.5 m and 3.0 m, respectively (see Fig. 4).

The key issue of the experiment design in aquifers with highly transient flow conditions is orientation of observation wells with respect to injection well due to rapid changes of ground water flow direction and possible deviation of tracer mass to areas without any observation wells installed. Therefore, the central observations wells of the first and second row of observation wells i.e. OW-4 and OW-11 (see Fig. 4), needed to be more or less aligned with prevailing direction of ground water flow on the day of tracer injection. During summer period the changes in ground water flow direction are less pronounced then in early spring and late autumn, therefore summer was chosen as the most convenient time period for conducting tracer experiment. Accordingly, experiment was planned to start on July $4^{th}$ 2011. Identification of prevailing direction of ground water flow on July $4^{th}$ 2011 was a prerequisite which supposed to enable setting up the exact locations and orientation of observation wells with respect to injection well, so that OW-4 and OW-11 would be more or less aligned with prevailing direction of ground water flow. Therefore, a measurement protocol for identification of locations and orientation of observation wells with respect to injection well was established (see Chapter 2.2. for details).

Artificial tracer used in experiment was Uranine (Na-fluorescein). Uranine was chosen due to its favorable characteristics, primarily sorption behavior, toxicity and small required mass (Tab. 1). The total tracer mass needed was estimated based on water volume to be traced and the detection limit of the tracer while the sampling frequency was determined based on expected breakthrough times (see Chapters 2.5. and 2.6 for details).

Table 1 Summary of the characteristics of the fluorescent tracers (Leibundgut et al., 2009)

| Tracer | Ex/Em [nm] | Relative fluorescence yield | Detection limit [mg/m$^3$] | Toxicity | Solubility [g/l] (20°C) | Light sensitivity | Sorption behavior |
|---|---|---|---|---|---|---|---|
| Naphthionate | 325/40 | 18 | 0.2 | Harmless | 240 | High | Very good |
| Pyranine | 455/510 | 18 | 0.06 | Harmless | 350 | High | Good |
| Uranine | 491/516 | 100 | 0.001 | Harmless | 300 | High | Very good |
| Eosine | 515/540 | 11.4 | 0.01 | Harmless | 300 | Very high | Good |
| Amidorhodamine G | 530/555 | 32 | 0.005 | Sufficient | 3 | Low | Sufficient |
| Rhodamine B | 555/575 | 9.5 | 0.02 | Toxic | 3-20 | Low | Insufficient |
| Rhodamine WT | 561/586 | 10 | 0.02 | Toxic | 3-20 | Very low | Insufficient |
| Sulforhodamine B | 564/583 | 7 | 0.03 | Sufficient | 10 (10°C) | Low | Insufficient |

Tracer experiment was divided into the following 3 successive steps: (1) injection of Uranine solution (16 g of Uranine dissolved in 15 l of water), (2) injection of native water to push the Uranine solution away from the injection well (1 volume of injection well), (3) sample collection in 50 ml bottles (see Chapter 2.6 for details).

### 2.2. Boreholes location and orientation

Identification of location and orientation of observation wells with respect to injection well was done based on established measurement protocol (WT1.4, D1.2, Zagreb aquifer, UNIZG-RGNF). The aim of this monitoring program was to identify the location and orientation of the observation wells with respect to injection well in order to drill the observation wells as aligned as possible with ground water flow direction on the day of tracer injection. Potential sites for injection and observation borehole locations were preliminary determined based on topographic maps of scale 1:25000 and aerial photographs of scale 1:5000. Further analysis of aquifer geometry and lithologic composition of selected potential sites were performed on existing research reports of investigated area which resulted in narrowing the number of potential sites. Remaining sites were analyzed with respect to land ownership where cadastral parcels belonging to the City of Zagreb, Croatian Waters and Water Supply and Sewage Company were preferred due to less complicated procedure for obtaining required permits for drilling and conducting tracer experiment. Since the flow conditions were categorized as highly transient, especially in near vicinity of the Sava River, the boreholes supposed to be placed further away from the Sava River where changes in ground water levels as well as in ground water flow direction occur less rapidly. All sites which met the set requirements were checked on the field to confirm the accessibility for the drilling crew and the rigs and the best site was selected (Fig. 5).

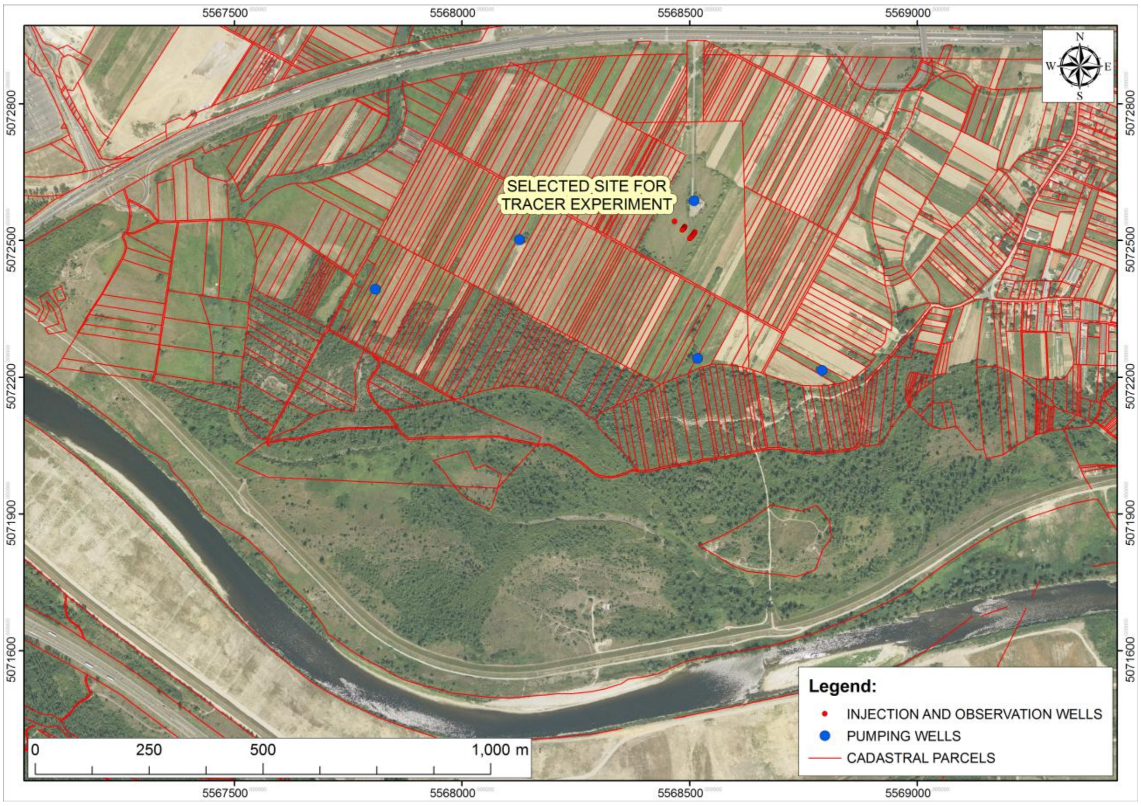


Figure 5 Selected site for injection and observation wells

Due to highly transient flow conditions where changes in ground water flow direction occur rapidly, all possible directions of ground water flow had to be established before drilling and installing the observation wells. Historical data of high and low Sava river elevations as well as ground water levels were analyzed for the past decade in order to establish the range of possible flow directions. The results showed that during high Sava river levels ground water flow direction is from SW to NE and during low Sava river levels the direction is from NW to SE. Historical directions of ground water flow in June and July were also analyzed for the past decade in order to narrow the possible ranges of ground water flow direction since the plan was to perform the experiment during June or July. Based on this analysis, preliminary locations of observation wells, i.e. their orientation with respect to injection well were determined. Beside analysis of historical measurements of ground water levels, real time ground water levels were also measured on hourly basis using water level loggers which were installed in surrounding observation wells (Fig. 6 a and b). Head contour maps created based on real time hourly water level measurements gave us insight into current ground water flow directions. Such daily analysis of flow directions started one month before the begging of the drilling and continued during the drilling process. Resulting head contour maps enabled control on determination of precise locations of observation wells and their orientation with respect to injection well and ground water flow direction (Fig. 7). Real time ground water level measurements and daily head contour analysis shown to be important in making small but vital shifts of preliminary determined borehole locations in order to drill the boreholes as aligned as possible with the ground water flow direction on the day of the tracer injection.

a) b)

Figure 6 Installing water level loggers in observation wells

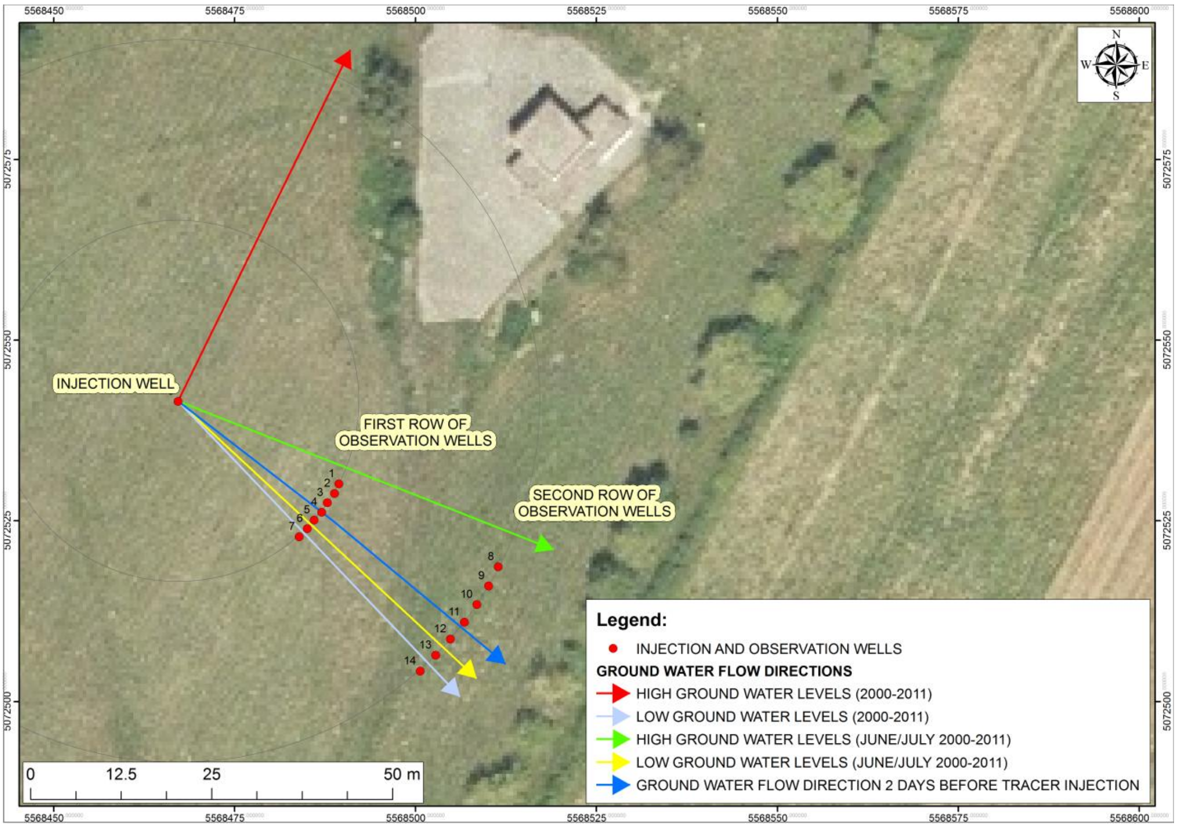


Figure 7 Orientation of observation wells with respect to injection well

### 2.3. Required permits for boreholes drilling and conducting tracer experiment

Due to Croatian legislation, namely Water Law, a permit had to be requested from Croatian Waters in order to drill the boreholes and conduct tracer experiment. The request for the permit had to be accompanied by the detailed research program. The process for obtaining required permit lasted one week, even though it can last up to two months, according to regulations of Croatian Waters. Therefore it is important to consider the time required for obtaining the required permits in planning of the tracer experiment time schedule.

### 2.4. Boreholes drilling, installation and cleaning of observation wells

15 boreholes 0,131 in diameter and 10 m deep were drilled. The drilling was performed using a spiral and a core apparatus (Fig. 8). Fully penetrating injection well and observation wells 0.075 m in diameter with a 5 m screen above the wells bottom were installed. Cleaning of injection and observation wells was performed by pumping the ground water with a pump until the water was clean and without turbidity (Fig. 9). The pumping rate was 0.4 l/s.

Figure 8 Drilling the boreholes

Figure 9 Cleaning of injection and observation wells

### 2.5. Tracer injection

On July 4th, 16 g of Uranine dissolved in 15 l of was injected into injection well (Fig. 10 a and b). The Uranine solution was prepared in the laboratory. The total tracer mass was estimated based on water volume to be traced and the detection limit of the tracer (Leibundgut et al., 2009). The calculation results have shown that a mass of 5 g would be adequate although the tracer could not be visually detected in samples. Therefore the decision was made to increase the Uranine mass to 16 g in order to get a slight visual detection of the Uranine in samples. The reason for increasing the mass of Uranine had more psychological than scientific nature. Due to long and exerting sampling campaign and involvement of students who's voluntary work made the sampling campaign possible, it was concluded that it is important to have a slight visual detection of the Uranine in samples in order to keep the morality of the students as well as the whole sampling team.

A funnel and a hose were used to inject the Uranine solution directly to the aquifer. The hose was slowly pulled up and down in order to distribute the Uranine solution as equally as possible through the whole thickness of the aquifer (Fig. 10 a and b).

After tracer injection, native water was injected in order to push the Uranine solution away from the injection well. The volume of injected native water equaled 1 volume of injection well.


a)


b)

Figure 10 Injection of Uranine solution

### 2.6. Sampling, sample storing and measurements of Uranine concentration

The sampling frequency (Tab. 2) was calculated based on expected breakthrough times. For the first row of observation wells distanced 25 m from injection well the sampling started 6 hours after tracer injection while for the second row of observation wells distanced 50 m from injection well the sampling started 12 hours after tracer injection. The sampling campaign lasted 40 days and ended on August 13th 2011. During 40 days of sampling, 1598 samples of ground water were taken. A team of seventeen people, working in groups of 2-4 persons in 8 hour shifts, was participating in an exerting 40 day/night/good weather/bad weather sampling campaign.

Table 2 Sampling frequency for the first (25 m) and second row (50 m) of observation wells

| | | | | | | |
|---|---|---|---|---|---|---|
| x = | 25 | m | | | | |
| Final schedule - summary of A, B, C and D scenario | | | | | | |
| Start after | 6 | hrs | | | | |
| 0 | - | 5 | d | 1 sample / | 3 | hrs |
| 5 | - | 10 | d | 1 sample / | 6 | hrs |
| 10 | - | 15 | d | 1 sample / | 12 | hrs |
| 15 | - | 20 | d | 1 sample / | 24 | hrs |
| | | | | | | |
| x = | 50 | m | | | | |
| Final schedule - summary of A, B, C and D scenario | | | | | | |
| Start after | 12 | hrs | | | | |
| 0 | - | 10 | d | 1 sample / | 3 | hrs |
| 10 | - | 20 | d | 1 sample / | 6 | hrs |
| 20 | - | 30 | d | 1 sample / | 12 | hrs |
| 30 | - | 40 | d | 1 sample / | 24 | hrs |

Sampling was done based on established measurement protocol (WT1.4, D1.2, Zagreb aquifer, UNIZG-RGNF). The aim of this sampling program was to ensure that ground water samples are taken as undisturbed as possible and as frequent as necessary. Ground water samples were taken using 12 V submersible pumps and stored in a 50 ml tagged bottles (Fig. 11 a and b). 12 V submersible pumps were used because they were easy to handle due to their low mass and they could be powered by a car battery without any other energy source. Besides, the small delivery rate of the pumps ensured minimal turbulences in water in observation wells and prevented turbidity in the samples. Immediately after each sampling, the bottles were stored in a black box in order to protect the samples from the light exposure. The pumps were cleaned after each sampling in order to minimize the possibility of transferring the tracer from one observation well to another (Fig. 12). Prior to lowering the pump in each observation well in order to take a sample, the pumps were submersed in a barrel containing water from local water supply system i.e. local hydrant and cleaned while running for the period of approximately 1 minute. Two barrels were used, one containing the clean water, and the other was empty and used for storing the water pumped from the barrel containing the clean water during the cleaning process. Used water was replaced with clean water after each sampling of all 14 observation wells. Local hydrant was used as a source for the clean water and barrels were transported using a Faculty car. For cleaning of the pumps, water was used instead of detergents due to large amount of detergent necessary and related high costs.

The Uranine concentration in samples was measured in the laboratory of the Croatian Geological Survey using LS 55 Perkin Elmer luminescence spectrometer with detection limit of 0.01 µg/l.

a)

b)

Figure 11 Ground water sampling


Figure 12 Cleaning of the pump after each sampling

## 3. Preliminary results

As seen on Fig. 7, ground water flow direction 2 days before tracer injection was almost aligned with the central observation wells OW-4 and OW-11, which was exactly as planned. Therefore, the tracer was expected to appear on observation wells 3, 4 and 5 and possibly on observation wells 6 and 7 since the ground water flow direction was slowly shifting to SE, as well as on observation wells 10, 11 and 12 and probably on observation wells 13 and 14.

Some 4.5 days after tracer injection the tracer was visually detected in ground water samples taken from observation wells 4 and 5. Slight green coloration was visible when ground water samples were compared with tap water. Samples from all 7 observation wells of the first row were immediately taken to laboratory which confirmed 0.14 and 0.19 µg/l of Uranine concentration in observation wells 4 and 5, respectively (Fig. 13). The samples from the rest of the observation wells contained no Uranine.

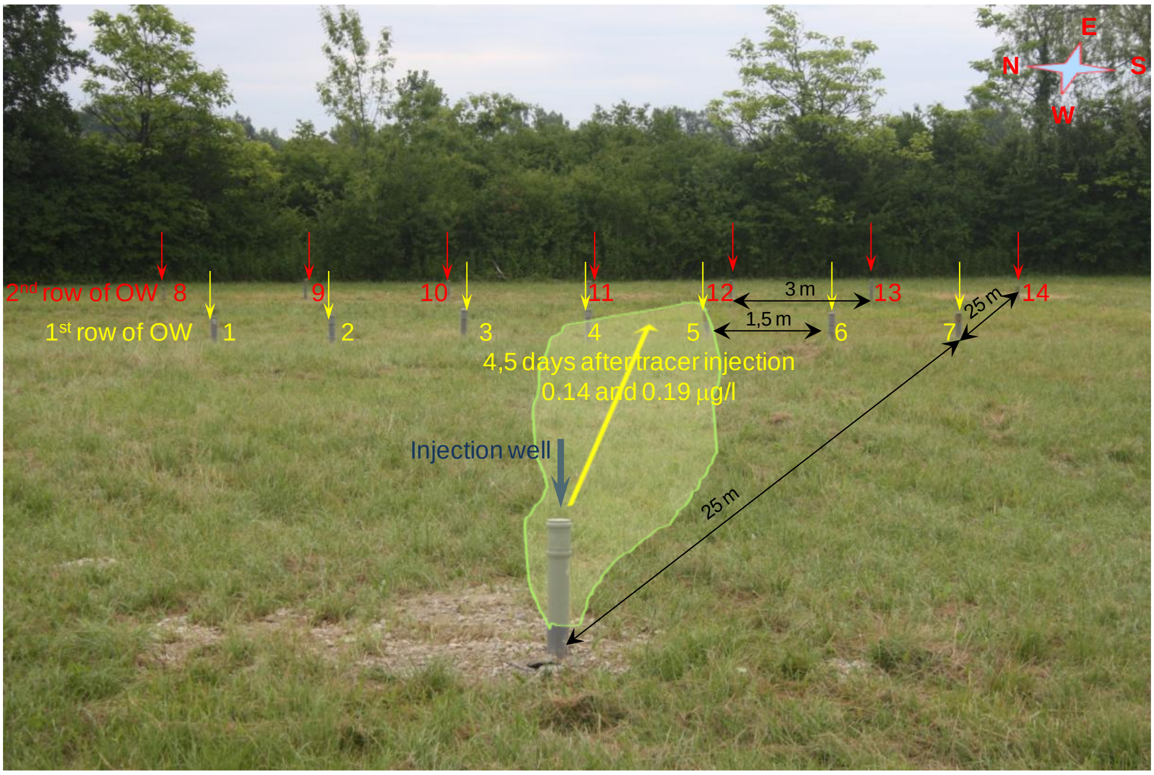

Figure 13 Appearance of Uranine tracer on OW-4 and OW-5 4.5 days after tracer injection

Since the experiment was going more or less as planned, the tracer was expected to reach the second row of observation wells in following 4.5 days. Due to continuous shifting of ground water flow direction to SE, the tracer occurrence was expected in observation wells 11, 12, 13 and 14.

The tracer appeared some 9 days after tracer injection as expected but in observation wells 8, 9, 10 and 11 and not in observation wells 12, 13 and 14. The tracer was also visually detected when ground water samples were compared with tap water. Samples from all 7 observation wells of the second row were as well immediately taken to the laboratory. Uranine was confirmed in observation wells 8, 9, 10 and 11 in concentrations of 29.9, 18.30, 17.31 and 0.96 µg/l, a far greater concentrations than observed in observation wells 4 and 5 some 4.5 days ago (Fig. 14). Larger concentrations in observation wells of the second row were also verified by visual inspection of the intensity of the green coloration in ground water samples. Samples taken from observation wells of the second row clearly had more intense green coloration than the samples taken from the first row of observation wells, i.e. observation wells 4 and 5.

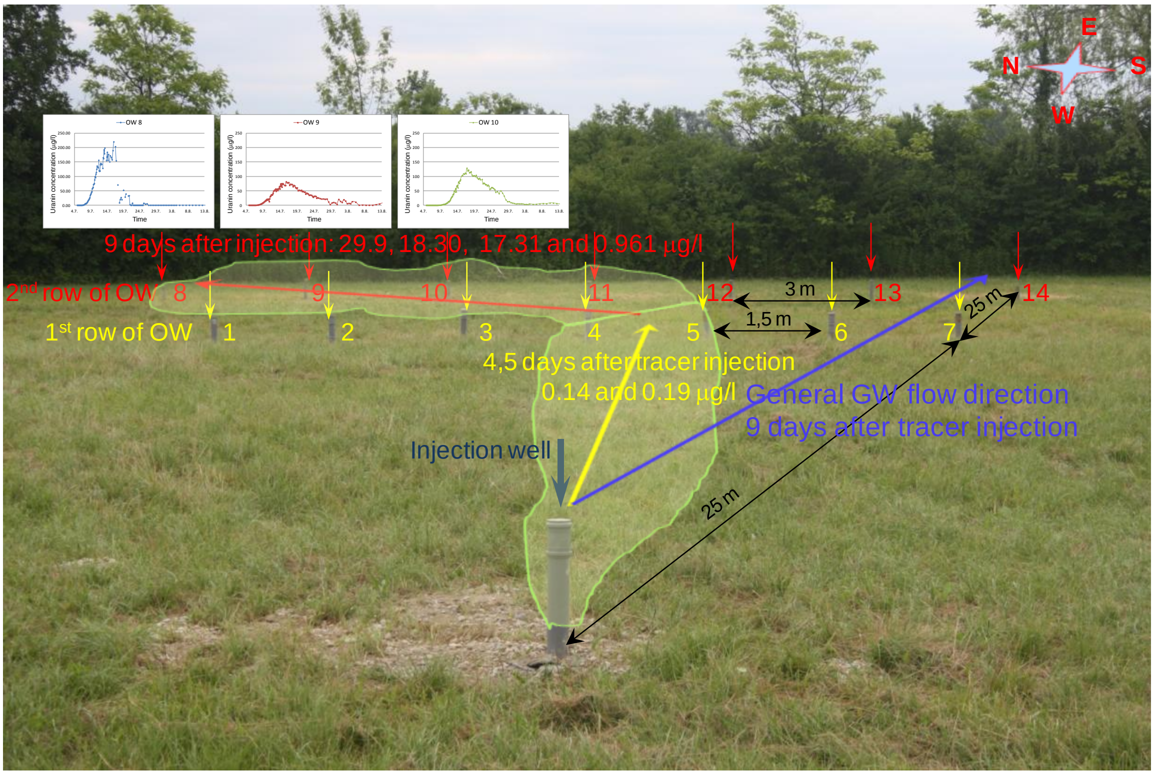


Figure 14 Appearance of Uranine tracer on OW-8 to OW-11 9 days after tracer injection

At the end of the tracer experiment, all samples were taken to the laboratory for measurements of Uranine concentration. Due to uncertainties associated with laboratory analysis, the final results contained breakthrough curves for observation wells 8, 9 and 10 only (Fig. 15, see also Fig. 14), while the rest of the laboratory results were rejected. Therefore the decision to increase the Uranine mass to 16 g in order to get a slight visual detection of the Uranine in ground water samples have proven as a good decision since it gave us insight into the direction of tracer migration through the first row of observation wells, i.e. observation wells 4 and 5.

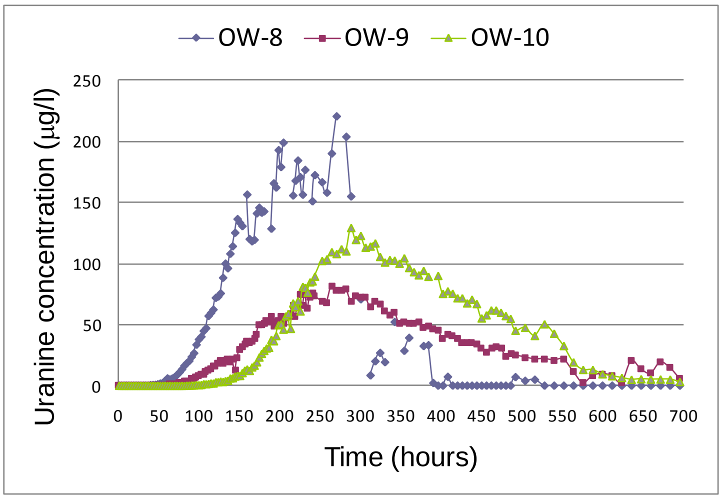


Figure 15 Observed Uranine concentrations in observation wells 8, 9 and 10

The results raised three major observations i.e. questions:

1. Tracer concentrations are evidently higher in observation wells of the second row which is distanced 50 m from the injection well than in observation wells of the first row which is distanced 25 m from the injection well, which is not in correlation with the theory of contaminant transport.
2. As shown on breakthrough curves for OW-8, OW-9 and OW-10 (see Fig. 15), Uranine concentrations are the highest in OW-8, somewhat lower in OW-9 and again somewhat higher in OW-10, which points out to anomalies in transversal dispersion which is is again not in correlation with the theory of contaminant transport.
3. As noted previously, tracer migration was not aligned with the general ground water flow direction since the tracer appeared in observation wells 8, 9, 10 and 11 instead of observation wells 12, 13 and 14 where it supposed to appear due to continuous shifting of the flow direction to SE during the experiment.

One of the possible explanations for the first two observations would include preferential flow paths through small paleomeanders or paleochannels with higher hydraulic conductivity. Regarding the third observation, probable explanation is that local deviations of the tracer migration direction from the general ground water flow direction are due to small scale of the experiment. Further to the east the tracer probably migrated according to the general ground water flow direction i.e. SE, which was generated based on larger scale measurements.

To additionally support possible explanation for the first two observations which included paleomeanders or paleochannels with higher hydraulic conductivity, the topographic maps from the 18$^{th}$ and 19$^{th}$ century as well as present day were acquired (Fig. 16, 17 and 18).

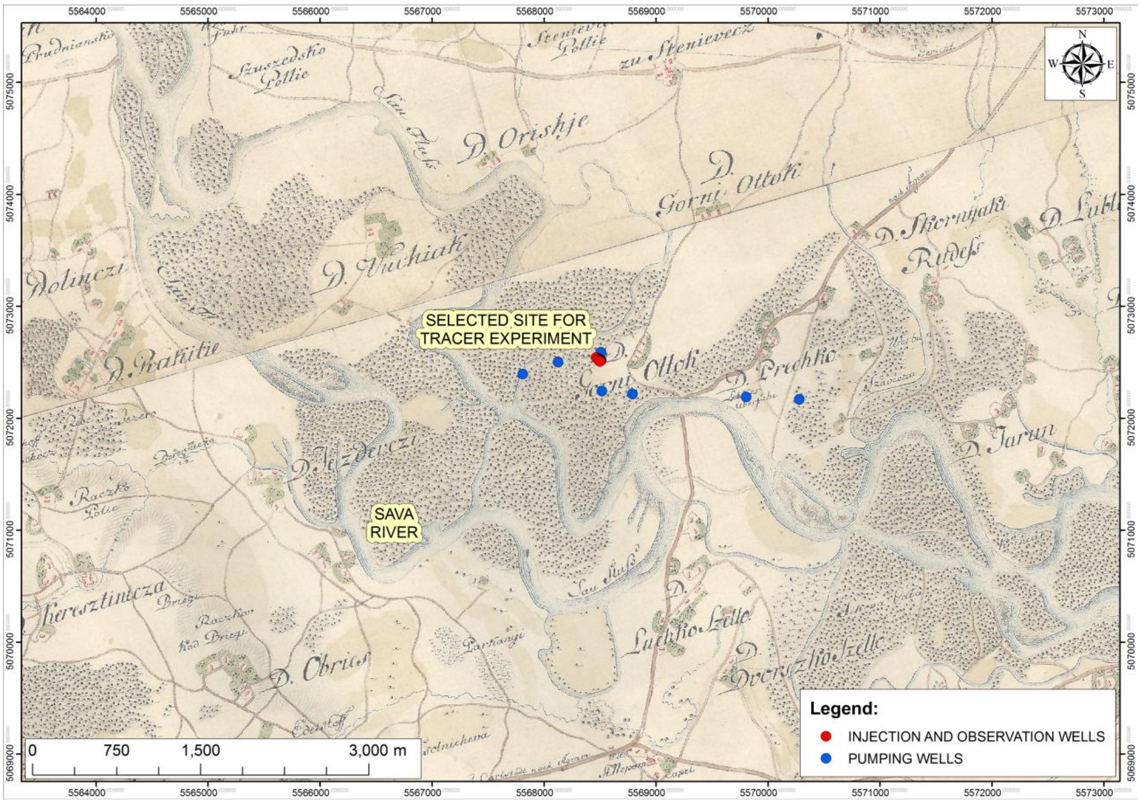


Figure 16 Topographic map showing historical Sava River courses on the site (year 1763-1787)

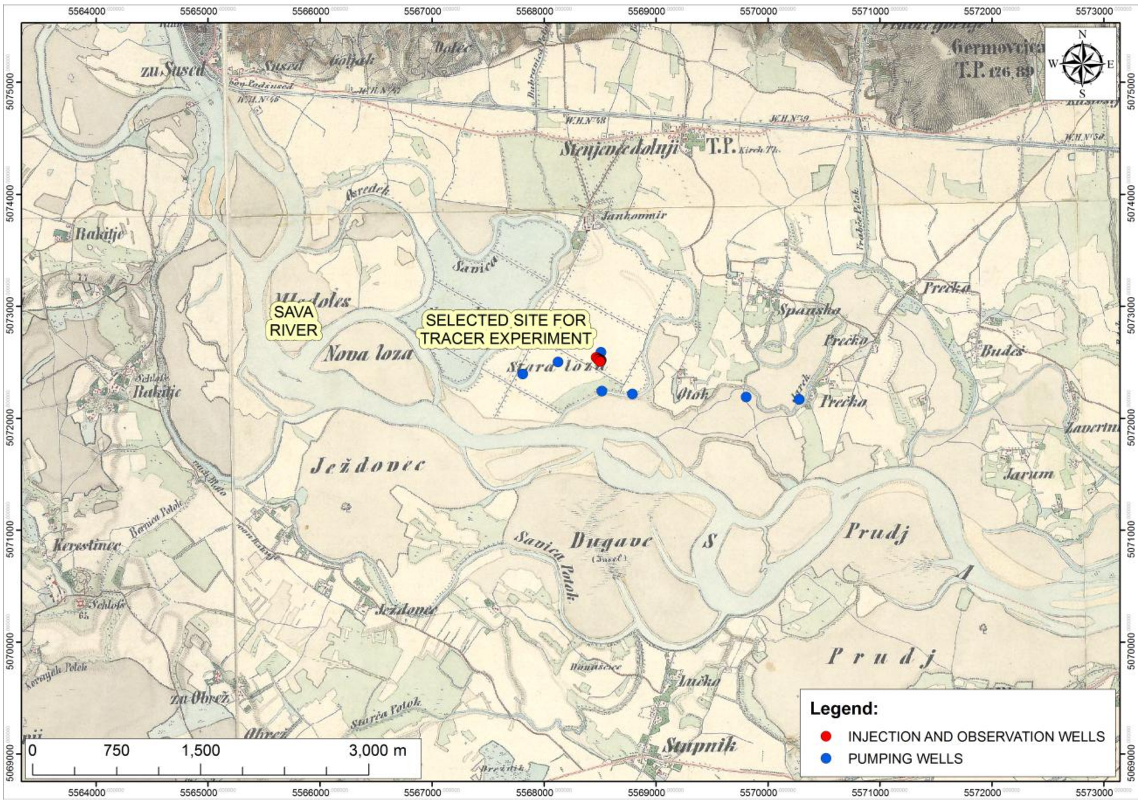


Figure 17 Topographic map showing historical Sava River courses on the site (year 1806-1869)

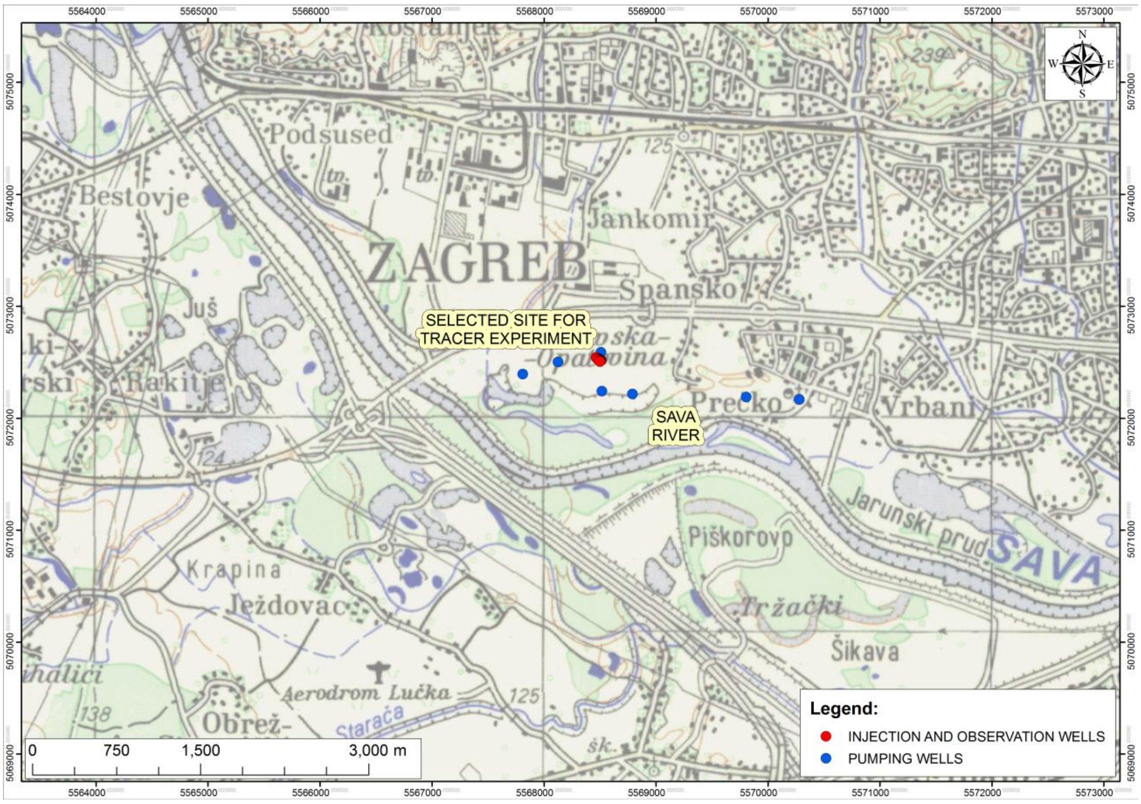


Figure 18 Topographic map showing present day Sava River course on the site

Historical topographic maps show that the Sava River had more than just one course on the site in 18th century. In 19th century the situation is also similar, while in present day the Sava River has only one main course. This shows that during the past 10000 years the Sava River must have had many smaller and larger courses where coarser material was deposited creating paleomenders and paleochannels with higher hydraulic conductivity.

Taken into account observations during the tracer experiment, the laboratory results, possible explanations of the three major observations of the results as well as historical topographic maps, preliminary conclusion would be that major part of the Uranine tracer bypassed the first row of observation wells possibly through small paleomeanders or paleochannels positioned north from the observation wells and appeared again on the observation wells 8, 9 and 10 which had the far greatest concentrations of Uranine tracer detected, both in laboratory as well as visually. A smaller portion of the Uranine tracer probably passed the first row of observation wells through OW-4 and OW-5 and appeared on OW-10 and OW-11 making Uranine concentrations on OW-10 somewhat higher. Such scenario would explain anomaly in transversal dispersion as noted in observation no. 2. This possible explanation is still not satisfactory due to lack of scientific evidence; therefore a further research including geophysics will be conducted (see Chapter 5.1).

# 4. Analytical modeling of Uranine breakthrough curves

## 4.1. Transport equation

Transport was considered as two dimensional (2D) since the tracer was injected through the whole thickness of the aquifer (see Chapter 2.5.). Therefore the vertical concentration gradient was presumed to be equal to zero, i.e.

$$\frac{\partial C}{\partial z} = 0 \tag{4-1}$$

Due to high estimated velocities (see Chapter 2.1.) the molecular diffusion was assumed to be negligible small. Taking all this into account and assuming that the x-axis was parallel to the flow direction, the transport equation can be written as

$$D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - v \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} \tag{4-2}$$

where ($x$, $y$) are the axis of the arbitrarily chose coordinate system; $C$ is the concentration of the solute in the water ($ML^{-3}$); $D_L$ and $D_T$ are the longitudinal and transverse dispersion coefficients ($L^2T^{-1}$); $v$ is the water velocity (L/T) and $t$ is time (T). $D_L$ and $D_T$ equal to (Scheidegger, 1961):

$$D_L = \alpha_L v \tag{4-3}$$

$$D_T = \alpha_T v \tag{4-4}$$

where $\alpha_L$ and $\alpha_T$ are the longitudinal and transverse dispersivities (L).

## 4.2. Solution to the transport equation

The solution to Equation (4-2) with initial and boundary conditions (4-5 to 4-7) is given by (4-8) (Lenda and Zuber, 1970).

$$C(x = 0, y = 0, t) = \frac{M}{nH} \delta(t)\delta(x)\delta(y) \tag{4-5}$$

$$C(x, y, t = 0) = 0 \tag{4-6}$$

$$\lim_{(x,y)\to\infty} C(x, y, t) = 0 \tag{4-7}$$

$$C(x,y,t)=\frac{M}{nH}\frac{x}{4\pi vt^2\sqrt{D_L D_T}}exp\left[-\frac{(x-vt)^2}{4D_L t}-\frac{y^2}{4D_T t}\right] \tag{4-8}$$

where $M$ is tracer mass (M), $n$ is the effective water porosity (–), $H$ is the mean thickness of the aquifer (L) and $\delta(x)$ and $\delta(y)$ are the Dirac space functions (1/L) in the $x$ and $y$ directions respectively.

The three parameters ($v$, $D_L$ and $D_T$) that need to be estimated in Equation (4-8) can only be found when observation wells in a tracer experiment are situated perpendicular to the flow direction (Leibundgut et al., 2009), and such conditions were more or less achieved in this tracer experiment (see Chapter 2.2. and Fig. 7).

The time distribution of the tracer in the observation well on the x axis (y=0) is derived from (4-8) by using $t_m$ and $C_m$ to be:

$$C(t)=C_m\left(\frac{t_m}{t}\right)^2 exp\left[-\frac{(x-vt)^2}{4D_L t}+\frac{(x-vt_m)^2}{4D_L t_m}\right] \tag{4-9}$$

where $C_m$ and $t_m$ are the peak concentration at the time of the appearance of that concentration. The values $v$ and $D_L$ from Equation (4-9) can be calculated using experimental data obtained from observation well on the x-axis (y=0). The only parameter left that needs to be obtained ($D_T$) can be derived from Equation (4-10) which describes the transverse distribution of the tracer concentration $C(y)$ observed at the flow distance ($x$) at time $t=t_m$:

$$C(y)=C_m exp\left[-\frac{y^2}{4D_T t_m}\right] \tag{4-10}$$

### 4.3. Estimation of the transport parameters

Estimation of the transport parameters was performed using the combined least square method (LSQM) integrated into user-friendly software FIELD (Maloszewski, P., Helmholtz Zentrum München, German Research Center for Environmental Health, Institute of Groundwater Ecology, 85764 Neuherberg, Germany). Transport parameters were estimated by fitting the 2D theoretical solution to observed experimental concentrations using a trial and error procedure. The fitting procedure started by fitting (4-9) in the observation well on the x-axis (y=0) and ended by fitting (4-10) to the transverse distribution of tracer concentrations. Beside trial and error procedure, Equation (4-9) can also be used in an automatic fitting procedure that combines the least square method with Taylor series approximation (Maloszewski, 1981).

Figures 19 to 22 show the fitted breakthrough curves from which transport parameters, i.e. $v$, $\alpha_L$ and $\alpha_T$ were calculated.

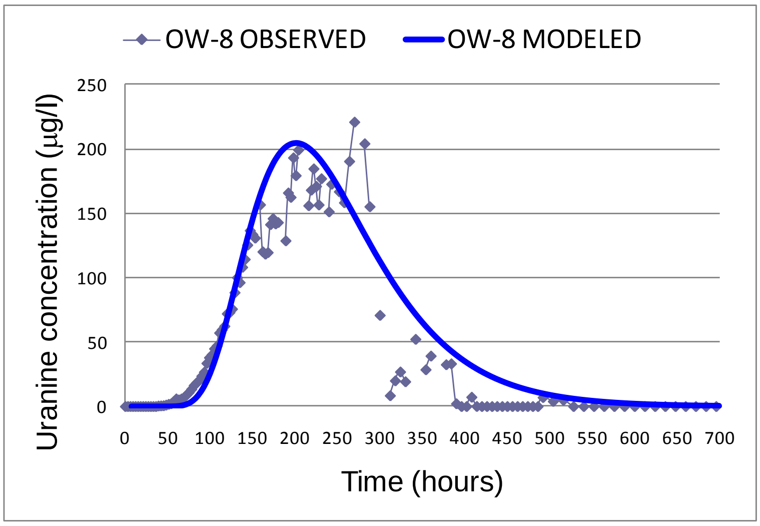


Figure 19 Fitted breakthrough curve for OW-8

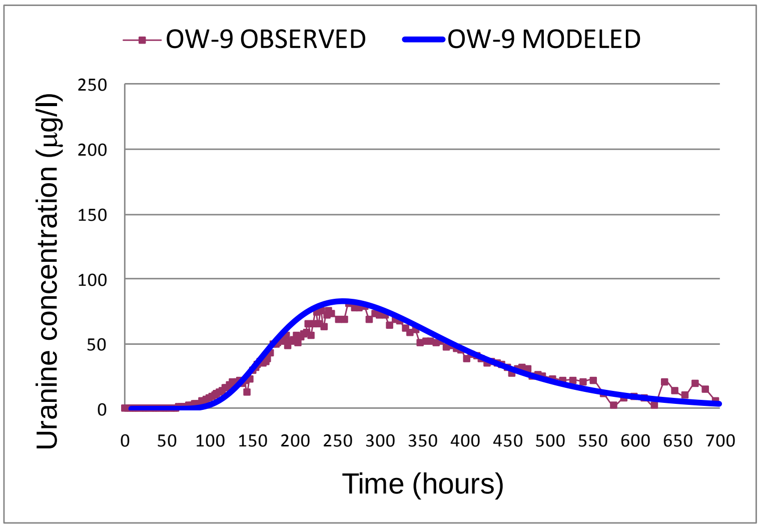


Figure 20 Fitted breakthrough curve for OW-9

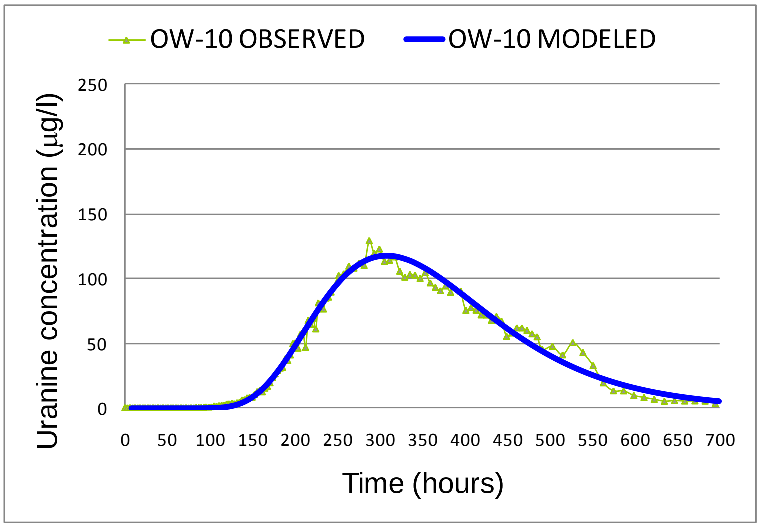


Figure 21 Fitted breakthrough curve for OW-10

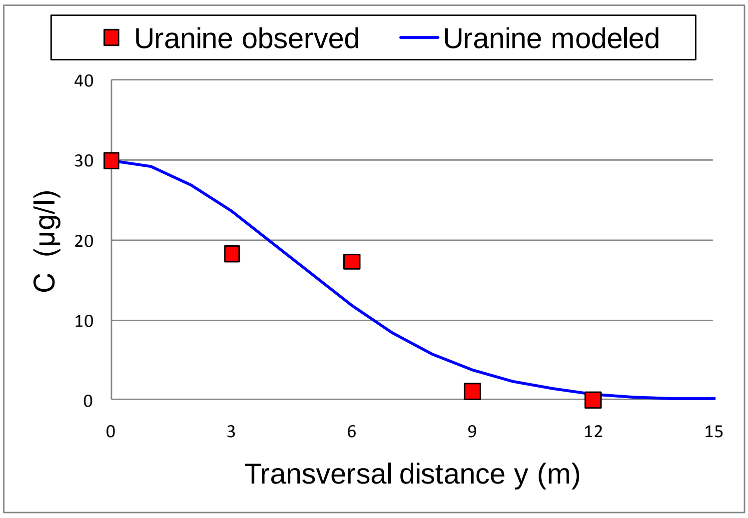


Figure 22 Fitted breakthrough curve - horizontal cross-section after 9 days (x=50m)

Transport parameters were calculated as follows: v $=$ 0.14 m/hr, $\alpha_L = 3.4\, m$ and $\alpha_T = 0.28\, m$.

## 5. Further research

As noted in Chapter 3, due to raised observations i.e. questions on results of tracer experiment and lack of scientific evidence on tracer migration path, a further research will include geophysical methods. Expectations are to get better understanding of heterogeneity of alluvial deposits and assumed preferential flow paths, i.e. probable tracer migration path. If the results of geophysical research will enable better understanding of the aquifer system and gave insight on probable tracer migration path, a numerical model will be build in order to estimate the transport parameters.

### 5.1. Geophysical research

Electrical methods, namely resistivity methods are generally applied in geophysical research of aquifers since measured resistivity depends on lythologic composition of deposits, its state i.e. compactness, fractures and porosity as well as the quality of the ground water (mineralization and salinity) (Šumanovac, 2007). 2D and 3D electrical tomography is planned to be applied in order to get better understanding of lateral changes in lythologic composition and hopefully detect preferential flow paths or paleomeanders i.e. paleochannels which would gave insight on probable tracer migration path.

2D electrical tomography with two electrical profiles which will cover approximately six times larger area than the actual research site (see Fig. 4 and 7), will be applied in the first phase of the research in order to detect possible zones on interest. 3D electrical tomography with at least five electrical profiles will be applied in the second phase of the research in order to get detailed insight into the zones of interest i.e. zones of assumed preferential flow paths or paleomeanders i.e. paleochannels.

### 5.2. Numerical model

Numerical model will be build with respect to obtained results from geophysical research. If applied geophysical methods will gave insight on lateral changes in lythologic composition and probable tracer migration path, general transport equation will be solved using numerical techniques, i.e. finite difference method (FDM) in order to estimate the transport parameters.

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