# Implementation of a 3D Groundwater Flow and Transport Model at the EUREX Plant in Saluggia (Northern Italy) by means of FEFLOW simulation

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**ABSTRACT:** *The EUREX plant (a former spent fuel reprocessing test plant built in the '60s) is part of Saluggia's Nuclear District, which also includes other nuclear installations (laboratories, storage facilities, etc.). The District is located 1.5 km upstream of the biggest well field in the region. A comprehensive groundwater monitoring program has been underway at the EUREX plant ever since 2004, when contaminated water was found inside the safety interspace around the spent fuel pool, and particularly since 2006, when anomalous concentrations of $^{90}Sr$ were found in groundwater. Thanks to the great amount of collected stratigraphic and hydrogeological data, it has been possible to implement a 3D groundwater flow model of the area. Moreover, the data collected for monitoring the concentration level of the $^{90}Sr$ also allowed to develop a 3D transport model of the Saluggia's area. This work shows a preliminary application of the FEFLOW (Finite Element subsurface FLOW system) software in order to evaluate the main physical and chemical processes involved in the radionuclides migration through the groundwater. The model was calibrated by FePEST (FEFLOW Parameter Estimation Software) in the steady - state flow regime by means of experimental available data. Then, the performances of the model have been tested taking into account a $^{90}Sr$ release from the EUREX pool in transient state flow in order to characterize the seepage from the pool into groundwater.*

## INTRODUCTION

EUREX (E*nriched* UR*anium* EX*traction*) is a former spent fuel reprocessing pilot plant built in the '60s that operated up to the early '80s (MTR and CANDU fuel types). It is part of Saluggia's Nuclear District, which also includes Avogadro (spent fuel repository) and Sorin (biomedical industry plus a nuclear waste repository). Just 1.5 km downstream of the district, the biggest well field of the region is located. It supplies drinking water for more than 100,000 people.
A comprehensive groundwater monitoring program (S.Iezzi, et. al., 2009) has been underway at the EUREX plant ever since 2004, when contaminated water was found inside the safety interspace around the spent fuel pool, and particularly since 2006, when anomalous concentrations of $^{90}Sr$ were found in shallow groundwater (0.02 Bq/l ≈ 0.5 pCi/l). The monitoring network was progressively extended and now more than 40 monitoring wells are available in the plant (a total of about 100 monitoring wells in all the area).
In June 2008 the decommissioning of the spent fuel pool was completed (spent fuel removal and transfer, pool cleaning, draining and purification of pool water). Afterwards, it was observed, during the monitoring activities, a persistent $^{90}Sr$ anomaly with a fluctuation according to the water table depth variation (monthly analyses; max. conc. 0.47 Bq/l ≈ 12.7 pCi/l). At the same time (2007-2008) the Environmental Authority found other contaminated ($^{90}Sr$, $^{60}Co$) wells outside the EUREX Plant, related to other leakages from the near plants.
In this context, it was mandatory to develop several groundwater models in order to make the monitoring activities more effective and credible. Moreover, a well calibrated model is able to provide forecasts for the future evolution, and to simulate the effects of unexpected events and also it could be the minimum base for possible MNA (Monitored Natural Attenuation).
This work shows the implementation at the EUREX plant of a 3D Groundwater Flow and Transport Model by means of the FEFLOW (Finite Element subsurface FLOW system) (DHI, web site) software. FEFLOW is an interactive finite-element simulation system for modeling 3D and 2D flow, age, mass, and heat transport processes in the groundwater and the vadose zone.
In Section 1, on the basis of the interpretation of the great amount of stratigraphic and hydrogeological data, a groundwater flow model was developed. As first step, the model flow was calibrated in a steady - state flow condition.

In Section 2, the FePEST (FEFLOW Parameter Estimation Software) (DHI web site) calibration tool of the hydraulic conductivity on the steady state flow model was performed. Then, a second FEFLOW model was developed for the EUREX plant (local model) at a more detailed scale. This because, inside the EUREX plant, the $^{90}Sr$ radionuclides migration occurred within a range of about 15 m and therefore it was necessary a more precision in the estimation of the groundwater flow around the pool.
In Section 3, once the PEST calibration was done on the local model, it was developed a transient state flow model in order to study the $^{90}Sr$ release from the pool. It was developed a $^{90}Sr$ transport model in the saturated zone both to test the performance of the software and to characterize the $^{90}Sr$ source term within the pool.
Finally, some conclusions were drawn.

**SECTION 1**

**Geological and Hydorgeological Framework**

The EUREX plant's area is located in Northern Italy, in Piedmont region, about 40 km Northeast from Turin, in the Saluggia district (Figure 1) (M. Rosati, et. al 2009), (Sogin S.p.A. (a), 2009), (R. Testoni et. al., 2015). In the South-West and West sides, the area is surrounded by the Dora Baltea river, while in the Southeast side by the Cavour channel and in the North-East side by a fluvioglacial terrace. The total area is about 6 km$^2$. The Dora Baltea flow regime changes from a minimum flow in winter to a maximum one in summer. The elevation of the top soil is in the range of 168-188 m above sea level.

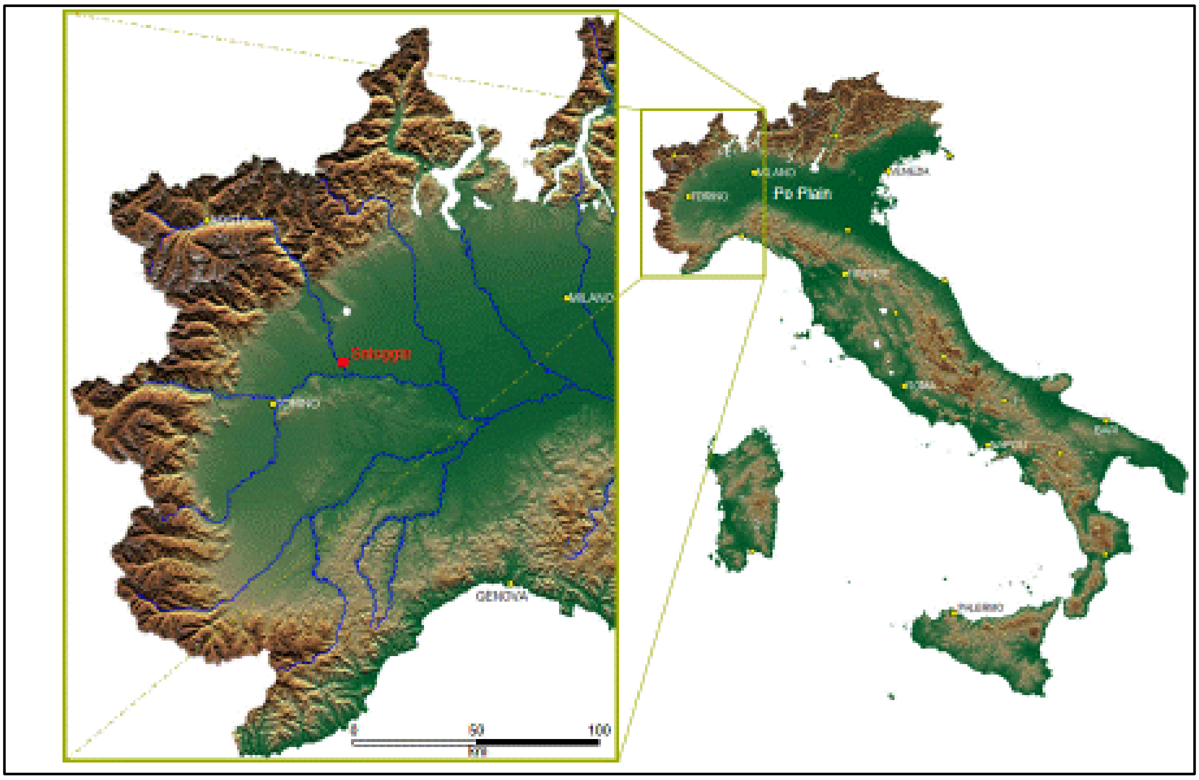


**Figure 1: Geographical localization of the EUREX plant's area in the Saluggia district.**

From a geological point of view, the EUREX site is located in the Holocene flood plain of the Dora Baltea river, laterally confined by Pleistocene fluvioglacial terraces. In the flood plain, alluvial deposits overlap fluvioglacial deposits, but their characteristics are quite similar. The local stratigraphy of the site is characterized by alternating layers of sand and gravel, with local interlayers of silt.

The hydrogeological system is featured by two main aquifers: the shallow aquifer and the deeper aquifer. They are separated by a silty layer. The shallow aquifer is located in sandy gravel and gravelly sand. It is strictly connected with the surface water of the river and irrigation channels. It is featured by a free water table. This aquifer is mostly recharged from water in moraine amphitheaters of the piedmont area and from leakages of waterways. Direct precipitation feeding of groundwater is just subordinate. Recharge from irrigation and paddy fields flooding occurs seasonally. Groundwater main flow direction is North-South, even if little variations take place locally because of stratigraphic features changing or due to waterway patterns. In EUREX surrounding area, Dora Baltea river provides the main drainage action; only during flood events the flow is inverted and the river temporarily recharge groundwater. The depth of free water table is between 10 m and 1-2 m. Below EUREX plant the depth of water table is 2-5 m and below spent fuel pool it is 3-4.5 m.

**FEFLOW Setup of the Steady - State Flow Model**

On the basis of the available data, the area was defined for the flow modeling in order to minimize the artificial effects of the boundary conditions that are fixed at the borders of the model.

For the steady - state flow model, the domain discretization has been done by triangular mesh with 122224 finite elements and 69957 nodes. The modelling area is about 8.06 km$^2$.

Figure 2 shows the 3D scheme of modelling area obtained through the interpretation of all stratigraphic data. From the hydrogeological point of view, this interpretation aimed to divide the whole of the domain into different layers characterized by homogenous permeability. The appropriate values of hydraulic conductivity were assigned to 6 layers, according to the available data (pumping tests, Lefranc tests, tracer test) and to literature data.

From top to down, as shown in Figure 2 it is possible to see the alluvial deposits of the Po plain (Quaternary) divided into various layers. The hydrogeological and stratigraphic characteristics are:

1. Gravel in sandy matrix (5-10 m thick), hydraulic conductivity: $K_{xy} = 10^{-4}$-$10^{-1}$ m/s. Initial value: $3 \cdot 10^{-3}$ m/s.
2. Fine sand, sometimes gravelly or silty (1-6 m thick), hydraulic conductivity: $K_{xy} = 10^{-6}$-$10^{-4}$ m/s. Initial value: $4 \cdot 10^{-5}$ m/s.
3. Gravel with sand (16-25 m thick), hydraulic conductivity: $K_{xy} = 10^{-4}$-$10^{-2}$ m/s. Initial value: $1.7 \cdot 10^{-3}$ m/s.
4. Sand with gravel (11-21 m thick), hydraulic conductivity: $K_{xy} = 10^{-6}$-$10^{-3}$ m/s. Initial value: $8 \cdot 10^{-4}$ m/s.
5. Silt, sometimes clayey or sandy (1-19 m thick, light blue layer in fig. 2), hydraulic conductivity: $K_{xy} = 10^{-7}$-$10^{-6}$ m/s. Initial value: $5 \cdot 10^{-7}$ m/s
6. Gravel with sand (more than 70 m thick), hydraulic conductivity: $K_{xy} = 10^{-4}$-$10^{-2}$ m/s. Initial value: $1 \cdot 10^{-3}$ m/s.

The first four layers of the shallow aquifer, while the layer 5 represents the aquiclude and the last one is the deep aquifer. In this paper, the study is focused only on the shallow aquifer, both because it is the main path for the radionuclide propagation into geosphere and it is also the most vulnerable.

For the shallow aquifer (conductivity zones from layer 1 to 4) the area was confined by assigning a set of Hydraulic Head BC conditions (with a gradient) at the upstream boundary of the Olocenic alluvial plain (terrace scarp), as can be seen in Figure 3. For the same layers, the downstream Hydraulic Head BC conditions were assigned to the Southern boundary and to the River boundary elements, located on the course of Dora Baltea river (see Figure 3 on right side).

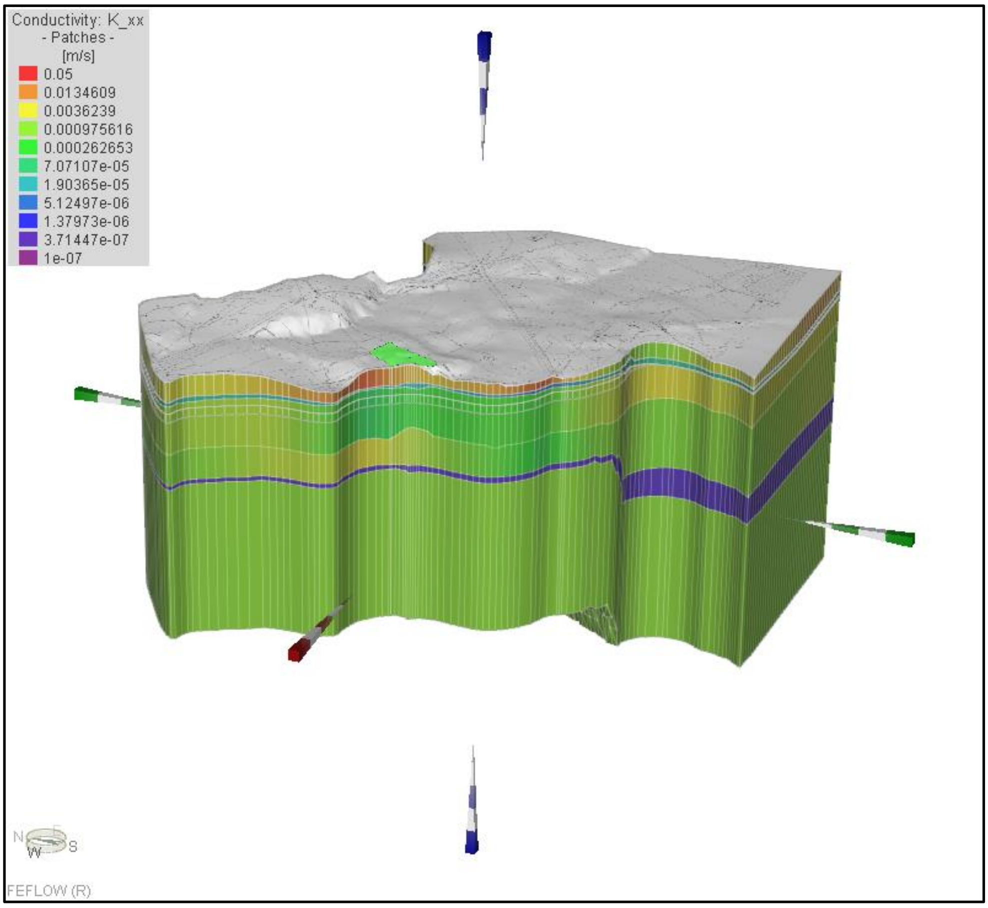


**Figure 2: Stratigraphic scheme of the area. Vertical exaggeration 15.8X.**

The gradient of the Hydraulic Head BC was obtained by a linear interpolation of several values of the head, located along the boundaries at fixed distance. Fixed values of hydraulic head on upstream and downstream boundaries have been chosen by an empirical and calibrated extrapolation of the piezometric pattern coming from the observations of 7 October 2008. The remaining hydraulic head values refer to the hydrographic levels of the Dora Baltea river measurements of the same day.

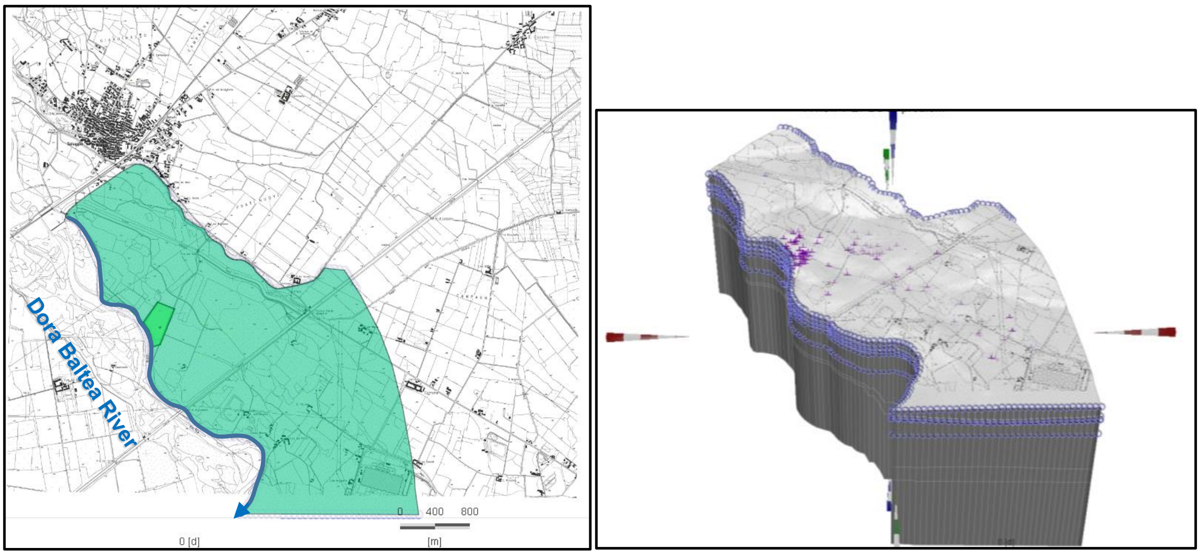


**Figure 3: 2D view of the domain and the boundaries of the model (left side). 3D view of the model (right side) with the Hydraulic Head BC (from layer 1 to 4, blue circles) assigned in upstream eastern boundary, in southern downstream boundary and in western river boundary, respectively.**

A concrete flood-defense wall was built around the EUREX plant (as it can be seen in Figure 4, left side). It is 0.80 m thick and 16 m deep on 3 sides and 12 m deep on the eastern side. In FEFLOW, the flood - defense wall was modelled, by adding a Supermesh polygon (0.80 m wide) with a very low hydraulic conductivity ($10^{-10}$ m/s). Moreover, in order to take into account the barrier effect of the wall on water flow, two additional layers have been added between third and fourth layer that represent the bases of wall foundations at different depths (16 m and 12 m). At last, another Supermesh polygon was added to represent the area where the EUREX pool is located, as showed in Figure 4, on the right side. Input phase was completed by inserting all the observations well data (filter depth, heads, etc.). A total of 89 wells were inserted. The wells distribution on the model domain can be seen in Figure 5.

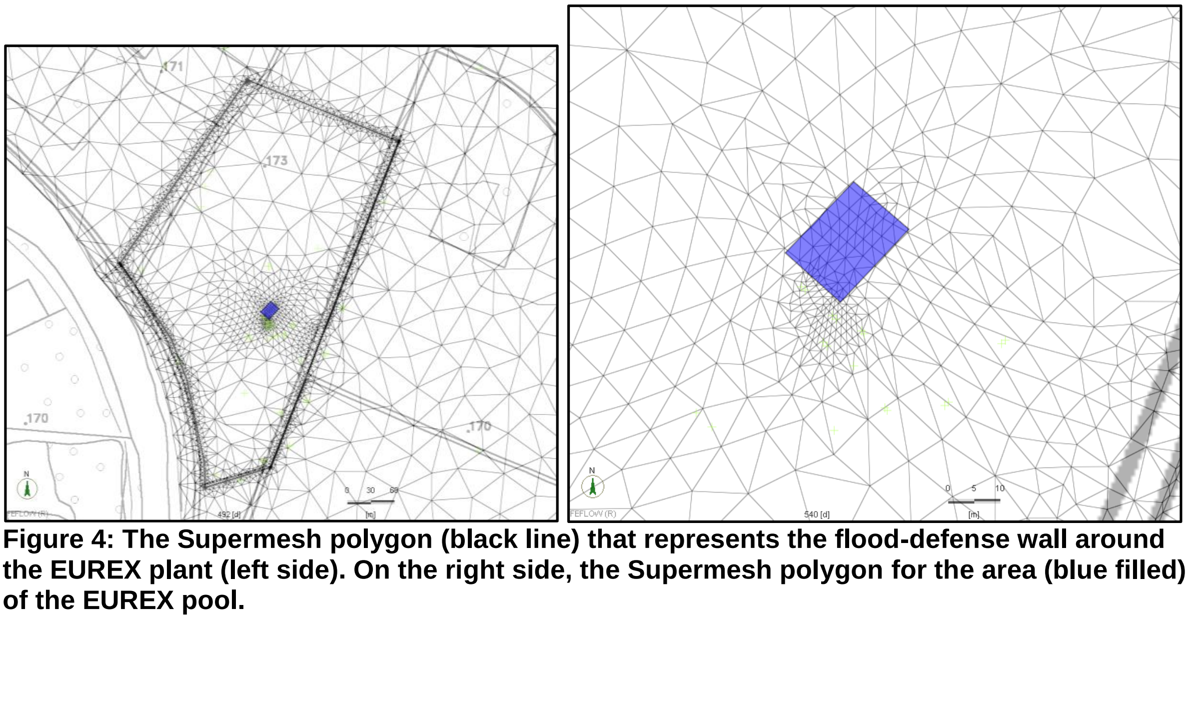


**Figure 4: The Supermesh polygon (black line) that represents the flood-defense wall around the EUREX plant (left side). On the right side, the Supermesh polygon for the area (blue filled) of the EUREX pool.**

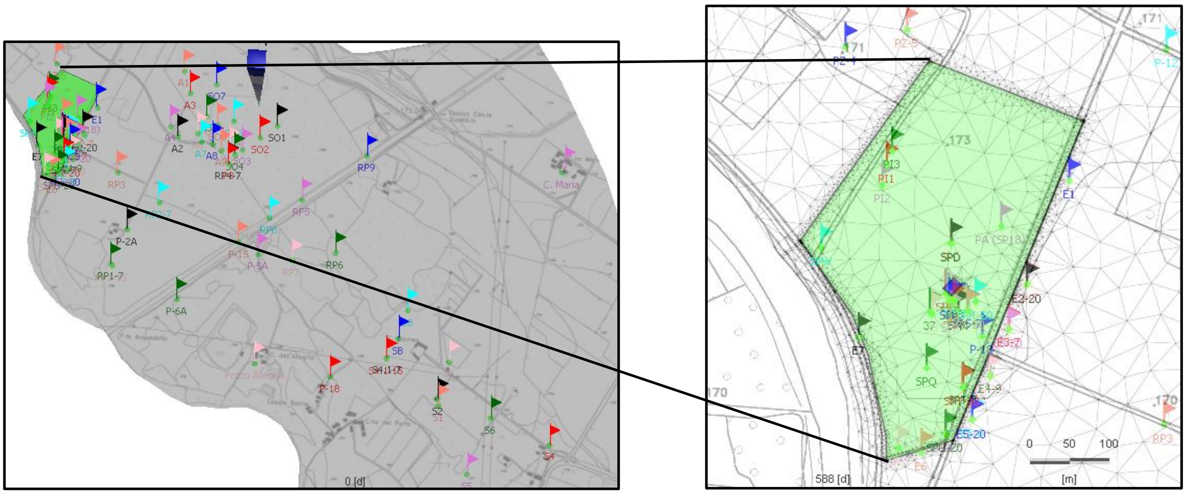

**Figure 5: Central part of the model domain with the observation wells of the shallow aquifer (left side); EUREX plant (right side).**

**Running the Steady State Flow Model**

After running the model in steady - state, the output has been taken as reference for its general calibration. The calculated heads were compared with the measured ones.

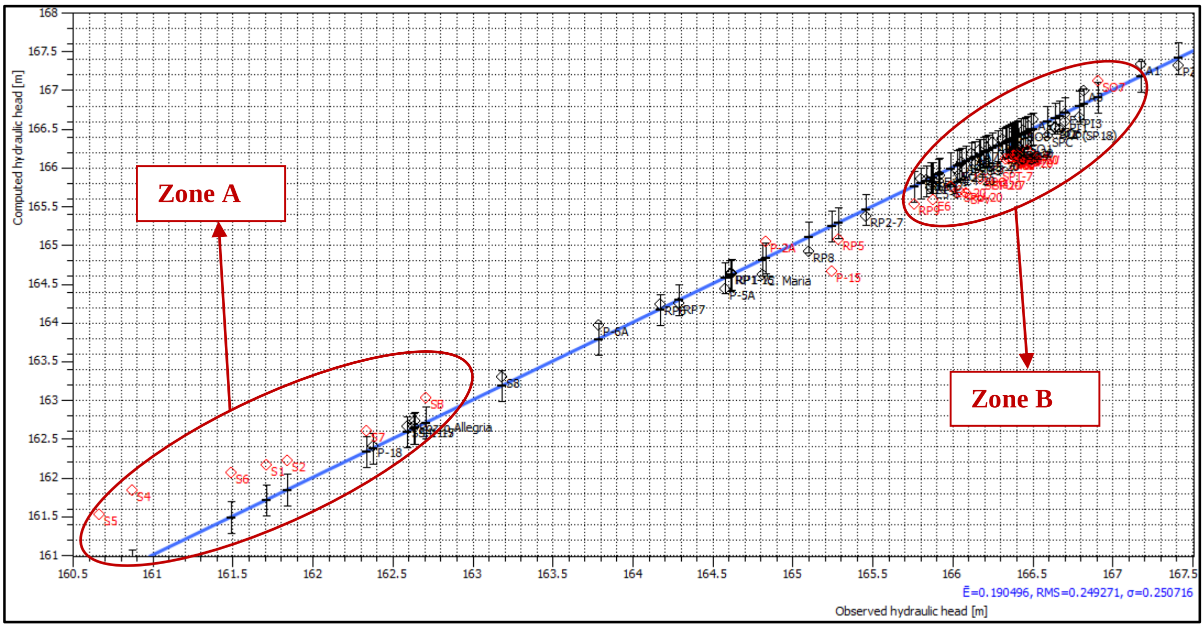


**Figure 6: Hydraulic Head Scatter Plot obtained by iterative manual calibration. The error bar values are equal to 0.2 m.**

Figure 6 shows the calibration plot obtained by the best combination between the hydraulic conductivity and the hydraulic head boundary conditions. The hydraulic conductivity for each layer was considered homogeneous by starting from their likely initial value. As can be seen in Figure 6, the differences between many observed and calculated values of the hydraulic head have still an unsatisfactory agreement, because they are outside of the error bar of 0.2 m (red points of Figure 6). Most of the discrepancies were obtained near the downstream boundary domain (zone A of Figure 6), below the EUREX plant and close and along the east direction respect to the flood defense wall (zone B of Figure 6). From a numerical point of view, these are critical areas, which have required a further calibration.
Instead of considering the homogenous values of conductivity, it was chosen to find an heterogeneous configuration of the conductivity field for each layer by using the FePEST tool, as shown in the next section.

**SECTION 2**

**FePEST Calibration of the Hydraulic Conductivity in Steady – State Flow**

FePEST is one of the most common software packages used for calibration of groundwater models. The previous FEFLOW model, calibrated by a "trial and error process", was imported within FePEST software in order to find an optimized configuration of the conductivity field for the first six layers.
For each layer, a pilot points interpolation method was used to get smoothed conductivity fields. For FePEST running, the following settings were considered:

- i) a total of 30 pilot points with Tikhonov Regularization were used for each layer;
- ii) the layers 3, 4 and 5 were unified into a single conductivity layer (the layers 4 and 5 were only defined to simulate the flood - defense wall);
- iii) initial values of conductivity have been obtained by the previous manual calibration;
- iv) the ranges of hydraulic conductivity for each layer were assigned on the basis of experimental investigation and of the geological features;
- v) the hydraulic head boundary conditions have been left fixed at the best value obtained by the same manual method;
- vi) all the others setting parameters were kept as default values;
- vii) the same observation points of the manual calibration, with the same weights equal to 1, were used.

Figure 7 shows the estimated heterogeneous conductivity field obtained by FePEST calibration for Layer 1.

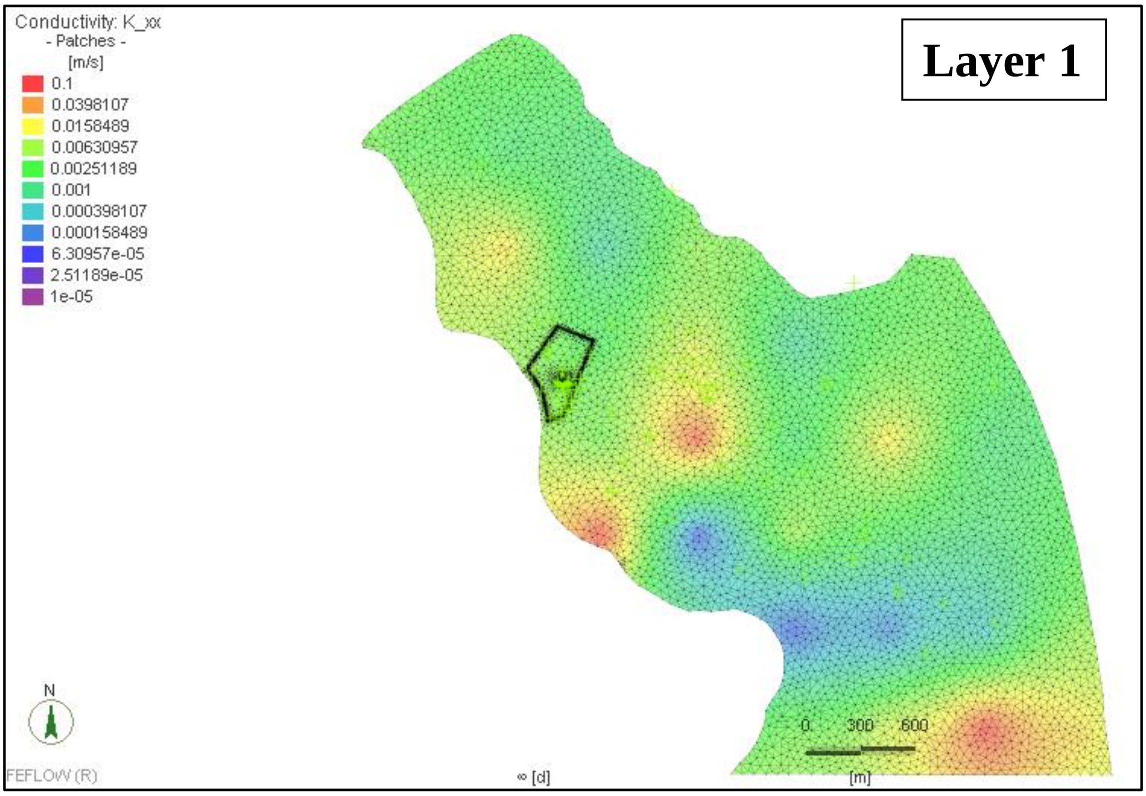

**Figure 7: Conductivity field for Layer 1 by FePEST calibration.**

**Running the Steady - State Flow Model Calibrated by FePEST**

After the FePEST calibration, the model was run again by reaching a satisfactory agreement between the calculated and experimental data of the shallow aquifer piezometric levels. Figure 9 shows this agreement. Most of the calculated values are within the tolerance range of ± 0.2 m of hydraulic head. The zones A and B, shown and discussed in Figure 6, do not represent the more critical areas for the steady - state flow calculation. The mean error achieved is about 0.041 with a standard deviation of about 0.059.

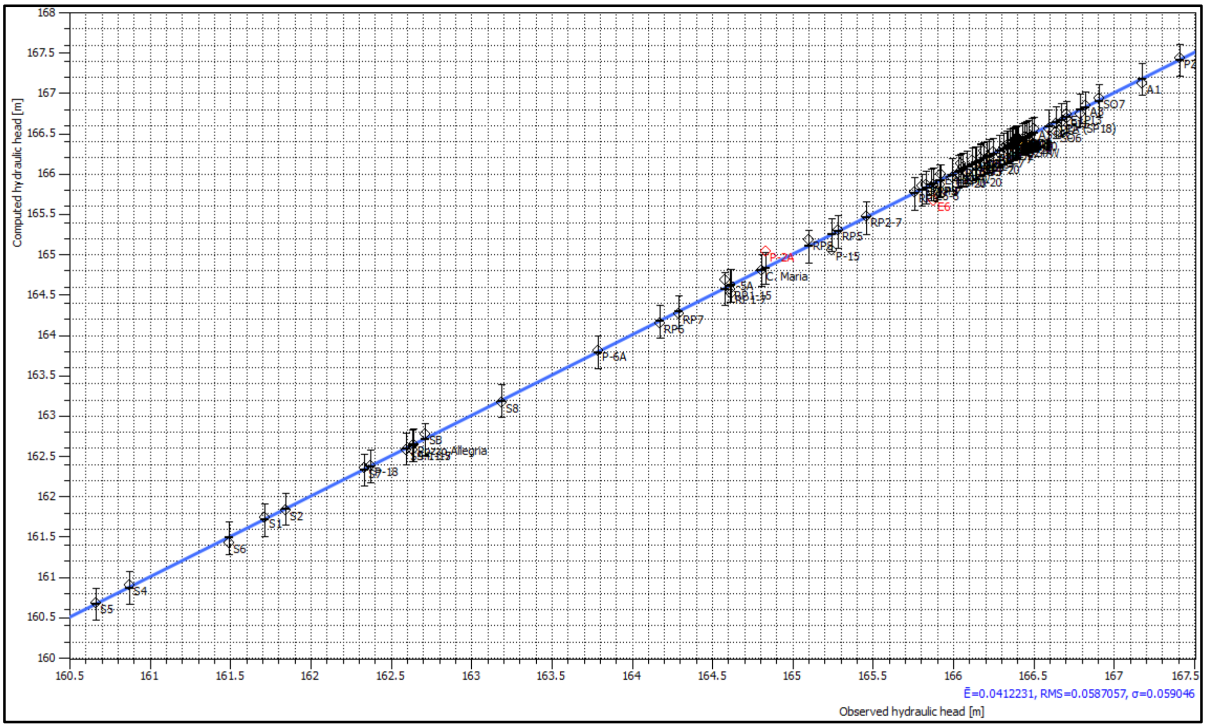


**Figure 9: Hydraulic Head Scatter Plot by FePEST calibration. The error bar values are equal to 0.2 m.**

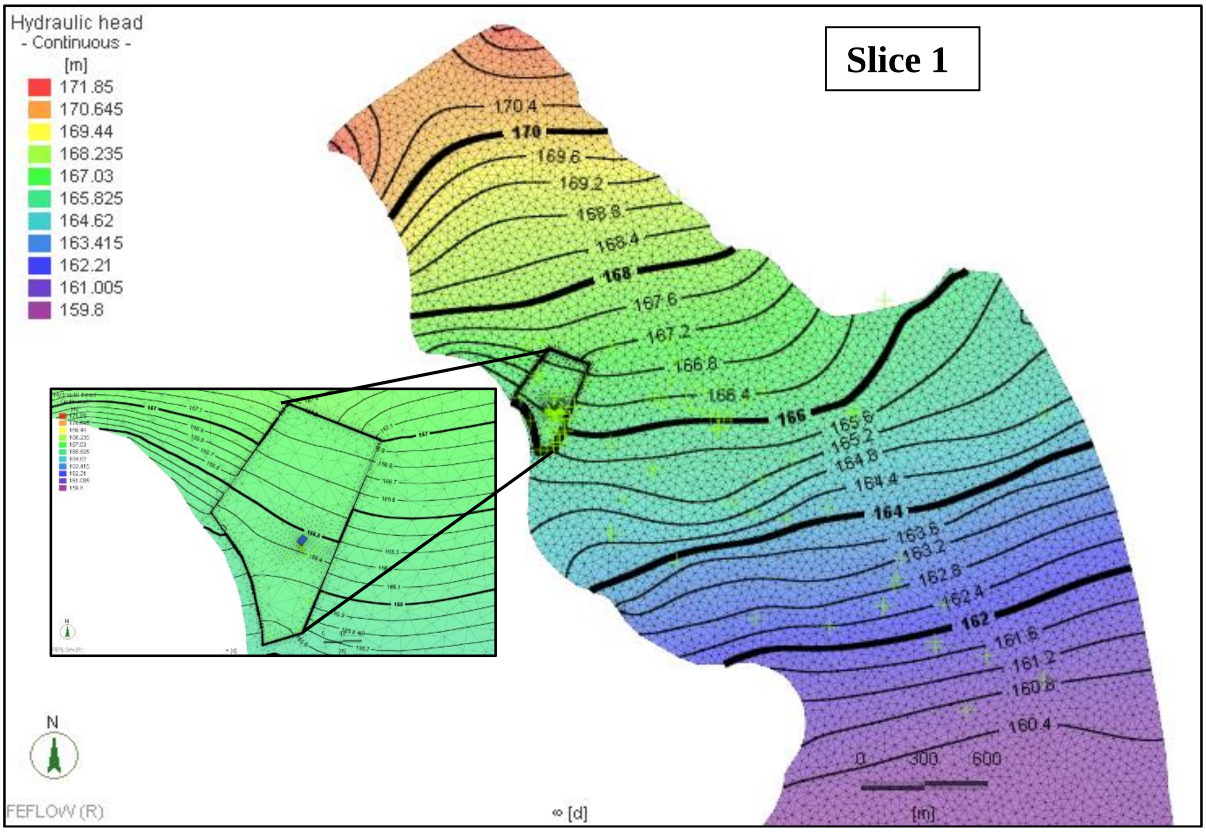


**Figure 10: Piezometric levels of the shallow aquifer in steady - state flow obtained from the calibrated model for the Slice 1.**

Figure 10 shows the isophreatic lines on the first slice obtained with the calibrated model. At the EUREX plant, their behavior is “broken” by the flood – defense wall. For the slices from 2 to 4, the behavior of the lines is quite similar. It means that the numerical model takes properly into account the hydraulic barrier effect of the flood - defense wall. Additional proofs of the model capability as regards this effect are shown in Figure 11 and 12. In Figure 11, i.e., the isophreatic lines are not affected by the flood - defense wall because the slice 6 is deeper than the wall itself.

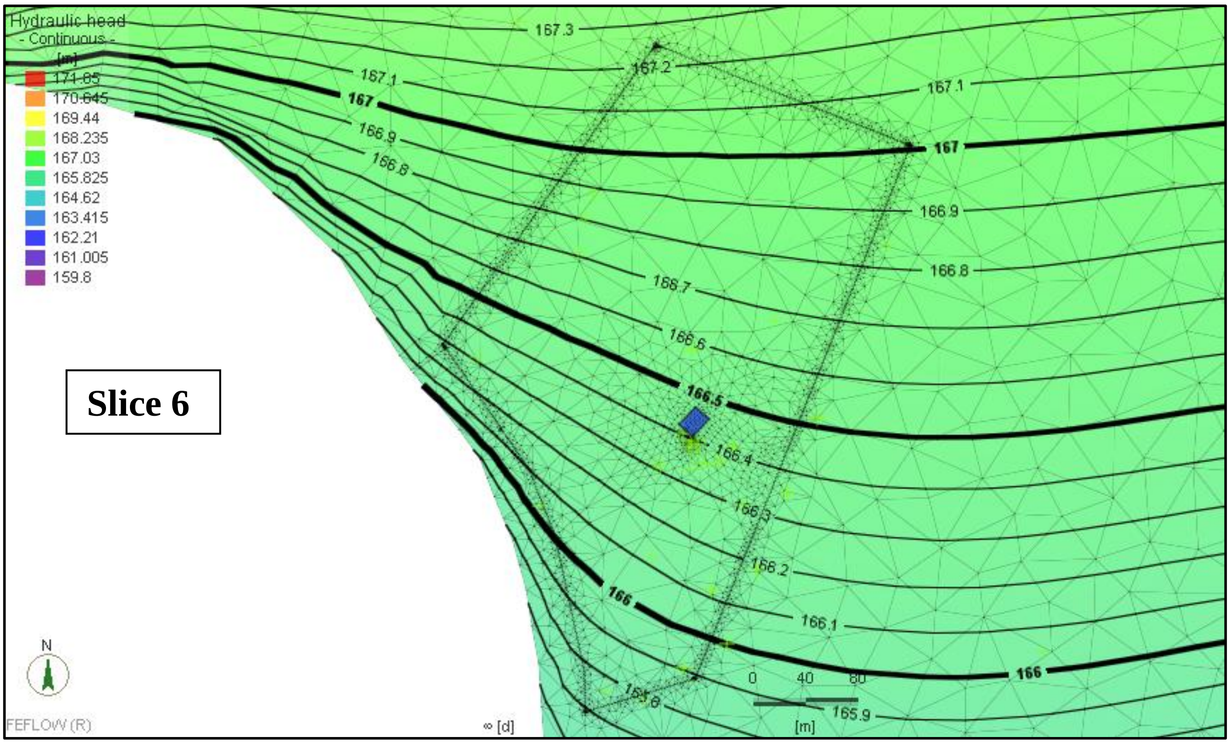


**Figure 11: Piezometric levels of the shallow aquifer in steady - state flow obtained from the calibrated model for the Slice 6. Figure shows a zoom in on the EUREX area.**

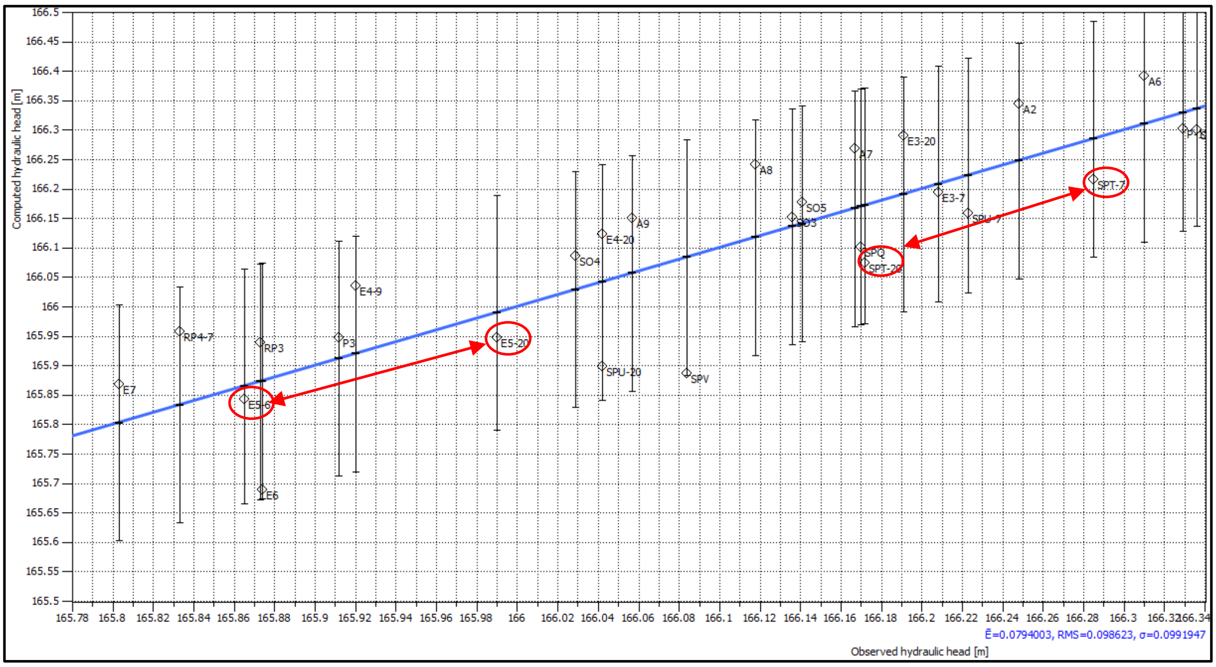


**Figure 12: Calibration plot in a steady - state. The red circles underline the hydraulic head of the couples of wells SPT/7 – SPT/20 and E5/6 – E5/20.**

Figure 12 shows the calibration plot for the two couples of wells, i.e., SPT/7 – SPT/20 and E5/6 – E5/20 (red circles). Their calculated values fit well the measured values, representing exactly the presence of the flood defense wall into the model. In fact, the wall mainly changes the piezometric levels of the shallow aquifer from higher to lower value, before and after it (see Figure 13), respectively (Sogin S.p.A. (b), 2009) due to the presence of the less permeable layer of silty sand (Layer 2 of the model) that is cut by the wall.

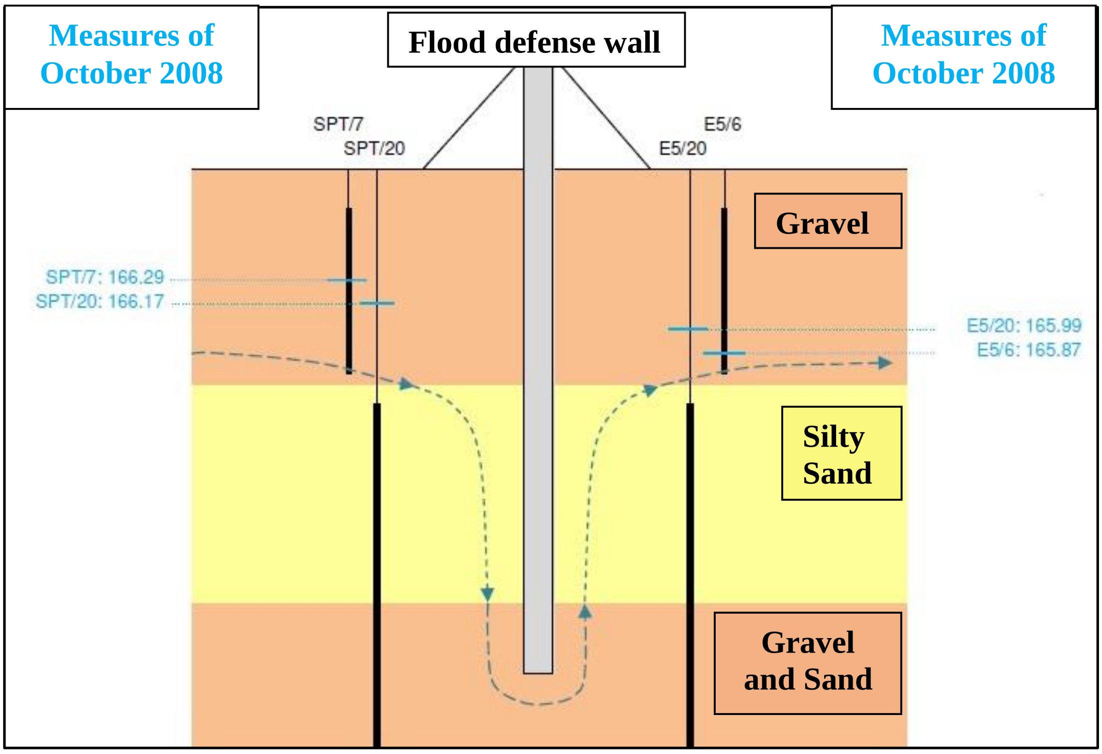


**Figure 13: Scheme (not in scale) of the main effect of the flood – defense wall (the thick black lines represent the different locations of the filters of the observation wells).**

**SECTION 3**

One of the network wells, called SPB, has been monitored for various years as regards the $^{90}Sr$ concentration (about two-monthly analyses). It was observed a direct correlation between water table fluctuation and $^{90}Sr$ concentration changes (S. Iezzi et. al., 2009). This relation is mainly observed in SPB well, likely because its closeness to the $^{90}Sr$ source: radionuclides coming from the pool are absorbed from the soil below the building, so when water table rises the soil is flushed and $^{90}Sr$ is discharged.
On the basis of the hydraulic information obtained in the previous section, a transient state flow transport model of the $^{90}Sr$ radionuclides was developed both to study the main physical and chemical parameters involved during the radionuclides migration and to characterize the $^{90}Sr$ source term inside the EUREX pool.

**FEFLOW Setup of the Transient - State Flow Model**

In order to setup the transport transient model, two other monitoring wells (SPG and PI3) were taken into account because equipped with logging depth sensors in the shallow aquifer. By comparing their data with the general piezometric picture of the model domain, it was possible to correlate their time series data with the variations of hydraulic head BC at the upstream north-eastern boundary and at the southern downstream boundary. The time variations of the boundary conditions concerning the water levels in the Dora Baltea river come from the sensor located few km downstream at Verolengo, that is part of the regional hydrological monitoring network (Arpa Piemonte Web Site), integrated with topographic surveys.
The simulation time of the transient state flow model goes from 5 March 2008 to 14 October 2009 with a total of 588 days.
As for the steady - state case, all boundary conditions were calculated by a linear interpolation of the hydraulic head values using the same fixed nodes and considering different values for different time, as estimated from the analysis of experimental data of wells SPG and PI3. All other parameters were left unchanged from the previous steady - state model.

**Running the Transient State Flow Model**

By running the transient - state flow model, the phreatic level was calculated for 588 days, starting from 5 October 2008. Figure 14 shows the comparison between the calculated phreatic levels in the SPG and PI3 wells and the observed ones, respectively.
By considering a tolerance of about 0.2 m on the hydraulic head, the calculated curve shows a good agreement with the experimental data. Because both wells are located near the riverside, they are strongly correlated with the behavior of the hydrographic levels of the river. Figure 15 shows the hydrometric levels of the Dora Baltea river during the entire period of the simulation. The obtained results are considered sufficiently accurate to try a first transport model for the $^{90}Sr$ source term released from the EUREX pool. A partial agreement of the curves at the highest or lowest peaks of Figure 15 (possibly related to a not complete knowledge of the whole conductivity field) is not considered essential, taking into account the scopes of this work.

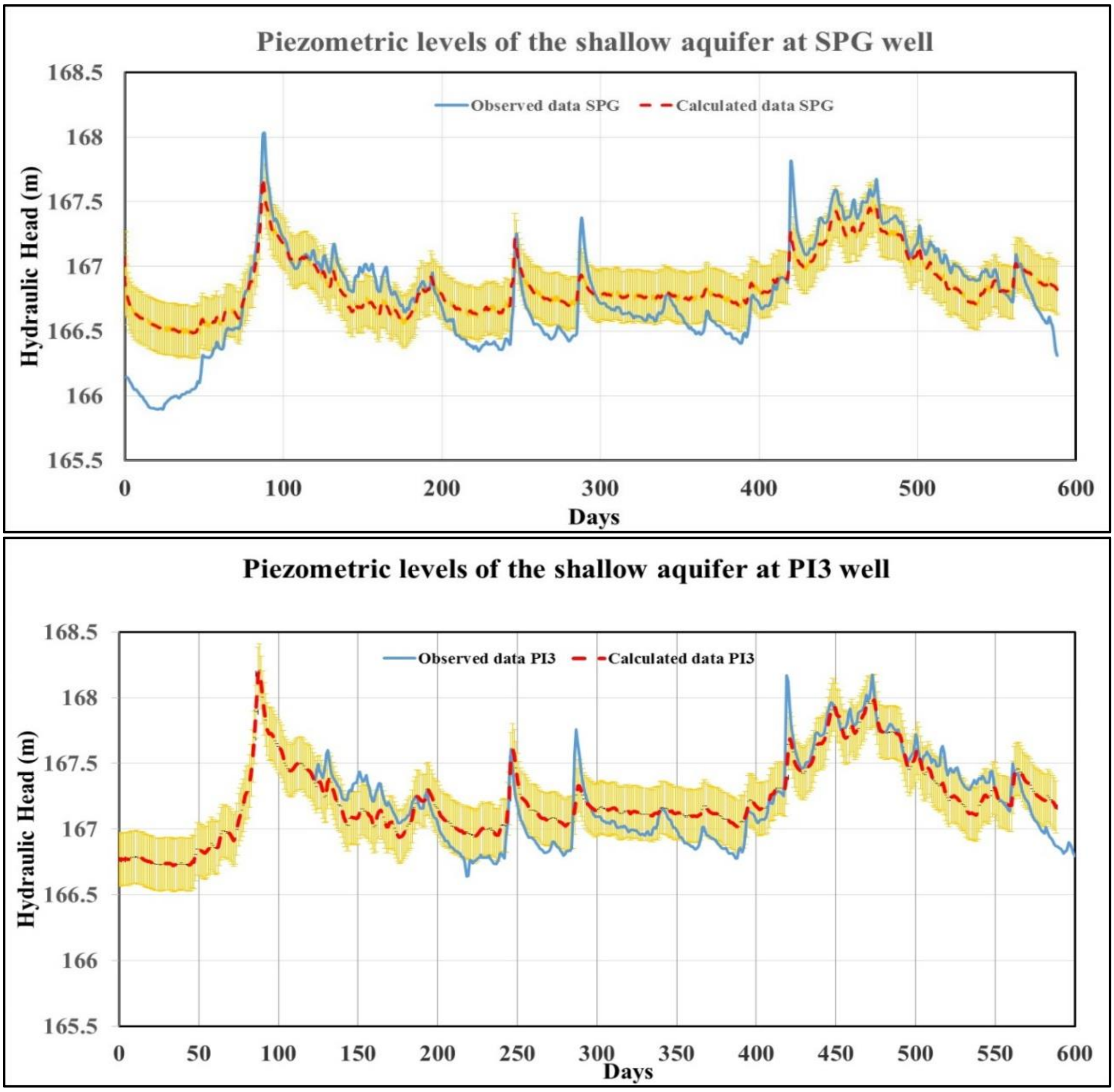


**Figure 14: Behavior of the hydraulic head at the SPG and PI3 wells (the PI3 time series starts at 100th day due to the lack of previous data). Comparison between calculated (red dashed line) values and measured data (blue line).**

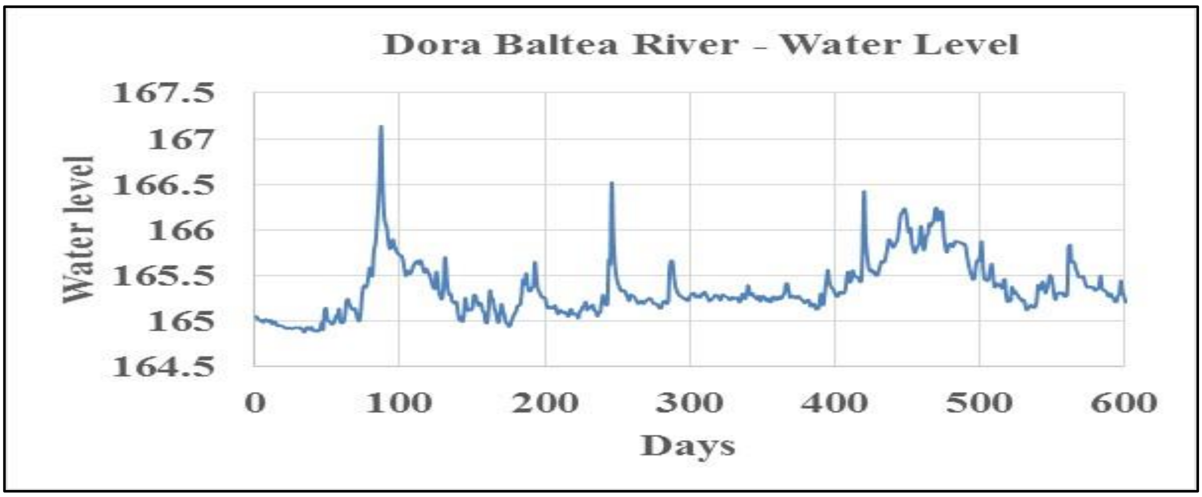


**Figure 15: Variation of the hydrographic levels of the Dora Baltea river at the point located near the flood defense wall.**

## Setup and Calibration of the FEFLOW local model

As said in the introduction, a more detailed hydrogeological "sub-model" was developed in order to improve the study of $^{90}Sr$ contamination referred to the SPB well, located about 15 m downstream the EUREX pool. Therefore, the study area was restricted to a smaller domain that implies an exact calculation of the groundwater flow around the EUREX pool.
The model overlays only the EUREX plant area, located within the flood – defense wall, as shown in Figure 16. The number of nodes was increased by a factor equal to about 8.5 (from 13410 to 116307 nodes) respect to the "macro-model". By means of this detailed mesh, it was possible to achieve a far better calibration (few centimeters between calculated and observed hydraulic heads). Moreover, it was added a new slice between the first and the second one in order to place the $^{90}Sr$ source at the right depth.
The boundary conditions used for this "sub-model" come from the hydraulic head values of the specific nodes, obtained by the previous steady - state "macro-model" regarding the whole Saluggia's area. Specifically, the boundary conditions were fixed just inside the plant area along the flood – defense – wall, as shown by the blues circles of Figure 16.
For the calibration, the same FePEST parameters of the previously cited calibration were used, except for the number of wells (only the wells inside the area were considered). The number of the pilot points for each layer was set equal to 20.
Figure 17 shows the results obtained after the FePEST calibration. On the left side of Figure 17, the scatter plot of the piezometric values shows a good agreement between the observed and the calculated ones. The mean error obtained is about 0.022 m with a standard deviation of about 0.037 (the error bars are set to 6 cm). On the right side, the same figure shows the calculated local groundwater flow that is in very good agreement with experimental values.

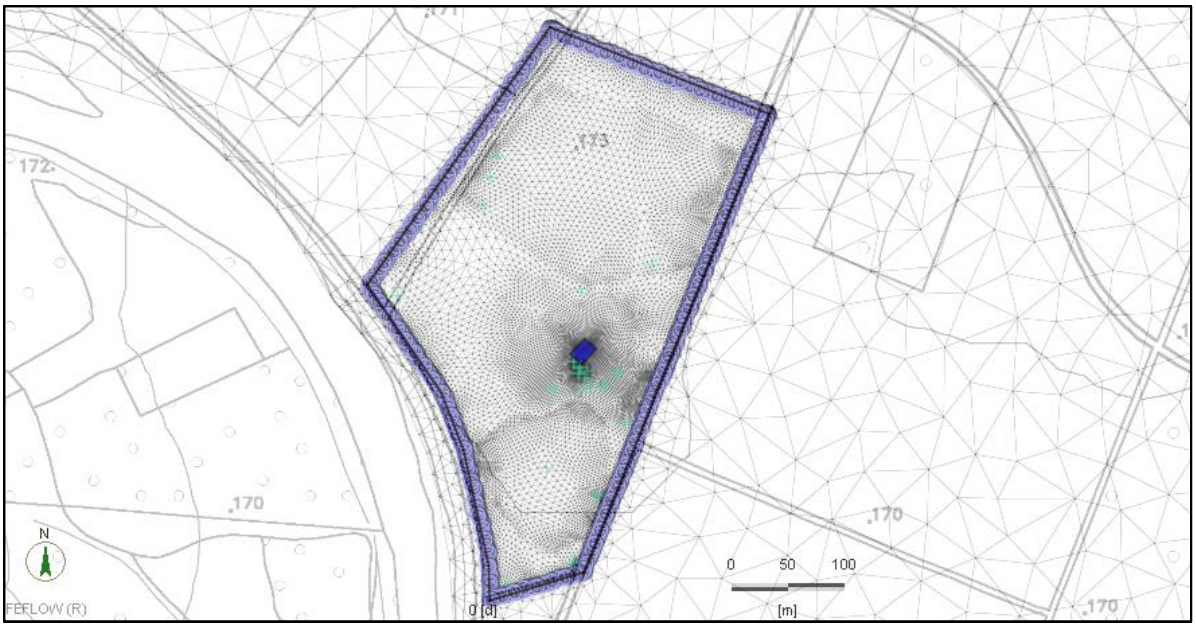


**Figure 16: Snapshot of the second detailed model of the EUREX's area. The blue circles are the new boundary conditions imported from the first macro model. The blue filled area is the EUREX pool.**

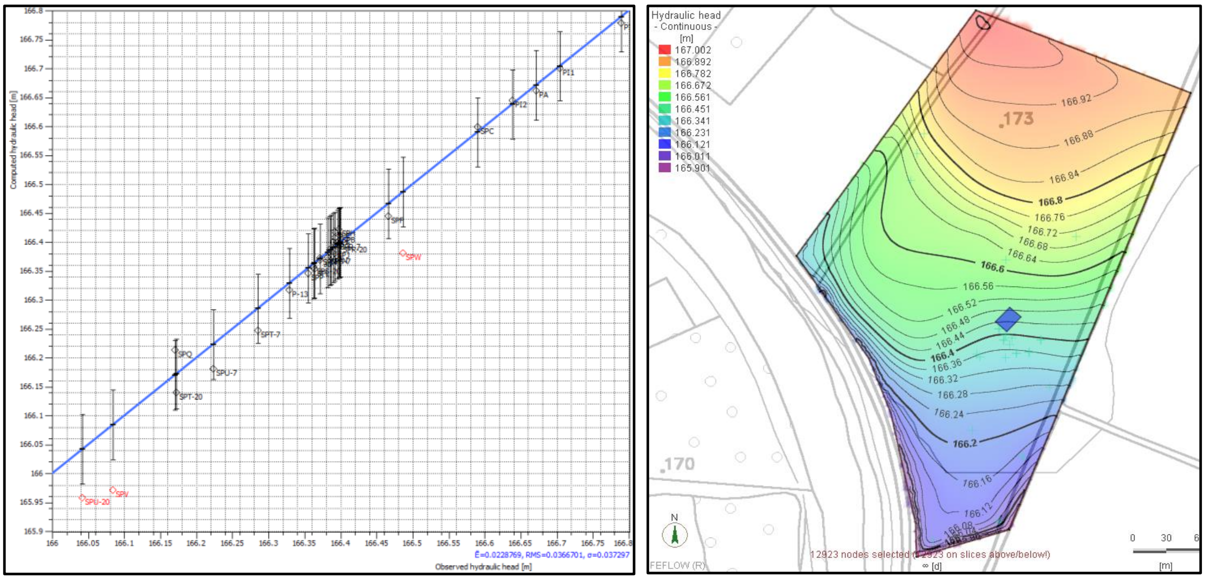

**Figure 17: Results obtained by means of FePEST calibration for the local model of the EUREX plant area. On the left side, the scatter plot of the piezometric levels. On the right side, the behavior of the isophreatic levels. The blue filled area represents the EUREX pool.**

Once again, on the basis of the results obtained by the FePEST calibration, a transient - state flow was developed for the local model. In this case, the boundary conditions time series (588 days) were taken from the macro model in transient flow state. The hydraulic head values obtained after the simulation and located at the same nodes (as shown by the blue circles of Figure 16) were replaced as new boundary conditions in the steady - state model.

### $^{90}$Sr Radionuclides Release and Transport

Many computational methods can be taken into account in order to characterize the release source (Cadini et. al., 2015). In this work, the release of $^{90}$Sr contaminated water in the soil underneath the EUREX pool was modeled with a 4$^{th}$ – kind mass transport boundary condition. In fact, it was impossible to have an exact characterization of the source in terms of concentration and release processes.
Moreover, the location of the release points and the extent of the leakage area are unknown. It means that the release of $^{90}$Sr directly into the groundwater could be modelled as a mass rate (grams per day).
The experimental data of $^{90}$Sr concentration, measured at different observation wells, showed a localized release of the $^{90}$Sr radionuclides, in particular, at the north-eastern corner of the pool (i.e., SPB well showed the $^{90}$Sr contamination while at the SPH well the contamination was negligible).
It was assumed that the $^{90}$Sr was instantaneously mixed into the groundwater and the effects of unsaturated zone were negligible. The SPB $^{90}$Sr observations also showed large fluctuations, likely correlated to the level of water table depth. In other words, it was hypothesized that the $^{90}$Sr release occurred when groundwater floods the bottom of the pool building where the contaminant was leaked through the cracks of the concrete.
Solute transport velocity depends on flow dynamics and on adsorption/desorption reactions which are expressed by partition coefficient Kd, i.e. the adsorbed concentration ratio between the solute concentration in water and in soil. Because Kd depends on several local factors, an accurate determination in the real transport environment is very important.
Mineralogical, sedimentological, chemical and physical analysis were carried out on soil samples in order to relate Kd values to the geologic and geochemical environment features.
Because of adsorption/desorption process changes in time, solution – soil contact time was also considered for the sake of transport real parameters. EUREX Chemical and Radiochemical Laboratory performed 200 chemical analyses and 220 gamma spectrometries for this work.
A results synthesis is exposed in (Sogin S.p.A. (b), 2009) which shows measured Kd values in relation to the solution – soil contact time. Measured values range adopted in this work is: [3.5-22]·10$^{-3}$ (m$^3$/kg) for $^{85}$Sr.
Table 1 shows the values of the main parameters used to characterize radionuclides release and transport into groundwater model:

| Parameter | Description | u.m. | Value |
|---|---|---|---|
| $\rho_b$ | Dry bulk density | $kg/m^3$ | 1800 |
| θ | Effective soil porosity | - | 0.25 |
| $\alpha_l$ | Longitudinal dispersivity in the aquifer | m | 5 |
| $\alpha_T$ | Transversal dispersivity in the aquifer | m | 0.5 |
| $D_{aq}$ | Molecular diffusion coefficient in the aquifer | $m^2/sec$ | $1 \cdot 10^{-9}$ |
| $K_{d1}$ | Distribution coefficient for layer 1 | $m^3/kg$ | $5 \cdot 10^{-3}$ |
| $K_{d2}$ | Distribution coefficient for layer 2 | $m^3/kg$ | $11 \cdot 10^{-3}$ |
| $K_{d3}$ | Distribution coefficient for layer 3,4 and 5 | $m^3/kg$ | $5 \cdot 10^{-3}$ |
| $K_{d4}$ | Distribution coefficient for layer 6 | $m^3/kg$ | $6.6 \cdot 10^{-3}$ |
| $K_{d5}$ | Distribution coefficient for layer 7 | $m^3/kg$ | $27.7 \cdot 10^{-3}$ |
| $K_{d6}$ | Distribution coefficient for layer 8 | $m^3/kg$ | $5 \cdot 10^{-3}$ |
| $\lambda_{90Sr}$ | Decay Constant for the $^{90}Sr$ | 1/s | $7.6296 \cdot 10^{-10}$ |

**Table 1: Hydrogeological parameters used in the FEFLOW model.**

As first approach, in order to characterize the $^{90}Sr$ release from the pool (as a leaching process), it was inserted a time series in the $4^{th}$ –kind mass transport BC that follows the same behavior of the water table. As it is possible to see in Figure 18, the $^{90}Sr$ release occurs by two different physical phenomena. The first one is a continuous release due to infiltration of contaminant through the concrete of the pool foundations until the groundwater (horizontal dashed red line), while the second one is a leaching process that occurs only when the water table reaches the bottom of the pool foundations. In this last case, the amount of $^{90}Sr$ released increases with the level of water that floods the bottom of the pool building.
From a numerical point of view, these processes can be modelled as follow:

i.) the water table variation observed at SPG was normalized in the range [0,1] between its minimum and maximum value, by obtaining a time series function of the hydraulic head (TSH) and then,
ii.) it was chosen an empirical function for the time series $^{90}Sr$ source (TSS), with the following proprieties:

$$TSS(TSH) = \begin{cases} 0.1, & if \quad TSH \leq 0.55 \\ TSS, & if \quad 0.55 < TSH \leq 0.8 \\ 0.8, & if \quad TSH > 0.8 \end{cases}$$

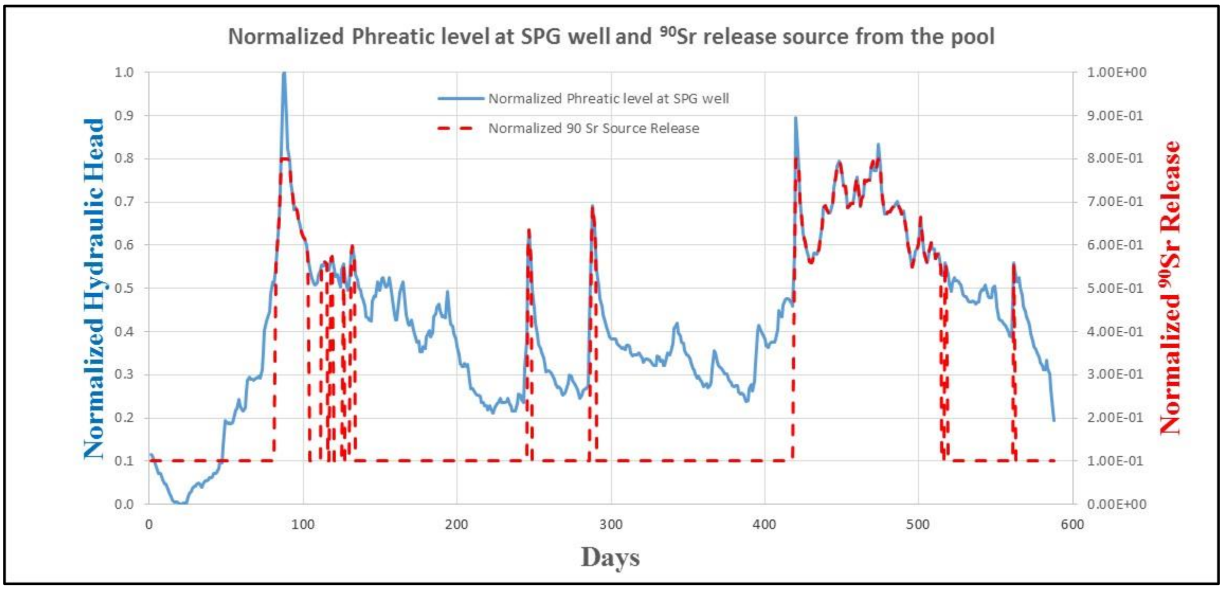


**Figure 18: Normalized phreatic levels observed at SPG well (blue line); and normalized $^{90}Sr$ source release due to leaching process by the shallow aquifer (red dashed line).**

The choice to cut the function TSH at 0.1, 0.55 and 0.8 values was due to a “trial and errors” calibration procedure with the observed and simulated $^{90}Sr$ levels at SPB well. In other words, in order to

characterize the contamination source at the bottom of the pool, it was followed the inverse process: the calibration of the source was done by using the experimental data of the radioactive concentrations of the $^{90}Sr$ detected at SPB well. To do this, it was also necessary to normalize both experimental values and the FEFLOW results between their minimum and maximum value, respectively. Moreover, the parameter values of Table 1 were also achieved by using the same "trial and errors" procedure.
The last figure shows the results obtained by FEFLOW transient flow simulation of the local model compared with the experimental ones.

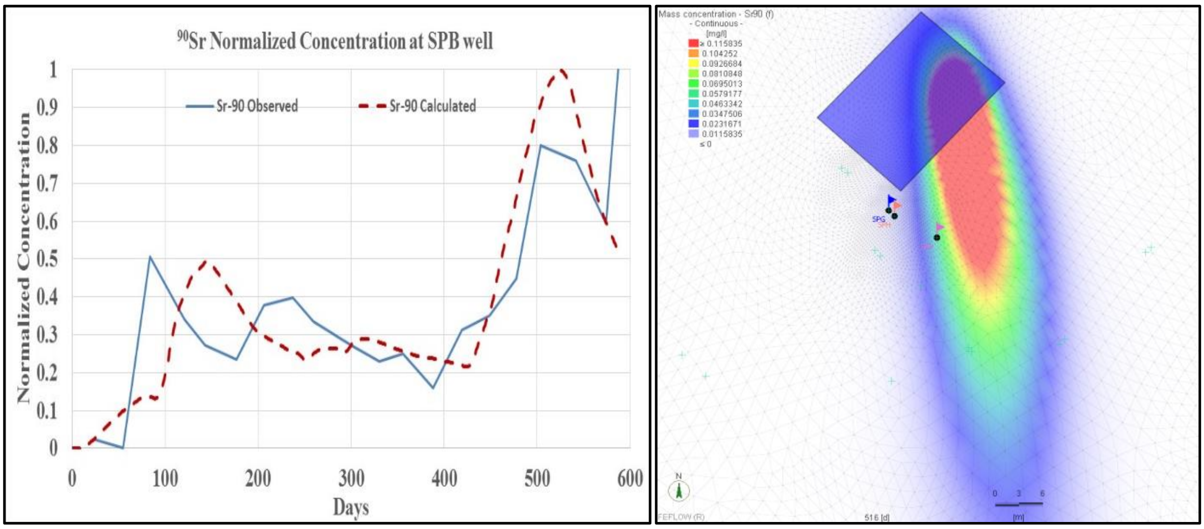


**Figure 18: On the left side: $^{90}Sr$ normalized concentration at SPB well both experimental data (blue line) and FEFLOW results (red dashed line). On the right side: $^{90}Sr$ contaminated plume released from EUREX pool (blue filled area), i.e. at the 516th simulation day.**

On the left side of Figure 18, the red dashed line represents the results obtained by FEFLOW simulation and it shows a satisfactory agreement with observations. Some minor differences can be seen about a delay of the first concentration peak in the calculated curve. It could be related to the uncertainties both on radionuclides migration processes through the concrete fractures in the pool foundations and on exact source location. Moreover, the simulation time starts during a transition period just after the emptying of the pool and therefore passing from a primary source to a secondary source (contaminated soil below the foundations of the pool) implying an approximation in the estimation of the injection rate of the contaminant into the groundwater system.
The picture on the right side of Figure 18 represents the plume propagation of the $^{90}Sr$ contamination at a given simulation time. As can be seen, only the well SPB located downstream respect to the SPH and SPG wells is intercepted by the contaminant. This can be taken as a further proof of the reliability and propriety of the numerical model.

## CONCLUSIONS

Thanks to a great knowledge of geological and hydro – geological site features, it was possible to make different complex numerical models of the Saluggia's site by using the FEFLOW and FePEST softwares. In particular, two different hydrogeological models were implemented at large and small scale in order to study the flow path of the shallow aquifer on the Saluggia's district and around the EUREX pool, respectively. Moreover, it was developed a transport model to characterize the release and propagation of the $^{90}Sr$ radionuclide around the EUREX pool in transient - state flow.
As first approach, it was performed a steady - state flow model on large scale and then, by using the FePEST tool calibration, it was found for each layer the likely heterogeneous conductivity field.
The results showed a good agreement with the observations.
Within the EUREX plant the effects due to the flood - defense wall on the isophreatic levels involves the implementation of a detailed model in a steady – state flow with a more refined mesh. A new calibration setup of the local model was found in order to get a closer agreement between calculations and observations. Once again, after calibration procedure, the new model setup was applied to a transient flow regime and for the $^{90}Sr$ radionuclides transport. The source term of $^{90}Sr$ release was modelled by a 4th boundary condition in order to simulate the leaching rate due to the flooding of the pool foundations by the water table of the shallow aquifer.

In order to find the best values of the main transport parameters (i.e., the partition coefficient, the longitudinal dispersion…etc.) and to better characterize the source function, it was used a “trial and errors” procedure. The results obtained in terms of normalized breakthrough curve show a good agreement with the experimental curve, measured at SPB well that is located close to the EUREX pool, demonstrating the high capability of the implemented model.

The slight discrepancies between the model results and the experimental ones suggest, for the future, some more detailed studies on, for example, the features of the river and of the irrigation channels or on the hydraulic conductivity field for each layer.

## REFERENCES


S. Iezzi, M. Imperi, M. Rosati, G. Ventura, Hydrogeological studies for radiological monitoring of shallow groundwater in EUREX plant of Saluggia (Vercelli, Italy), Radiat. Prot. Dosim., **137**, 3-4, 306, (2009).

http://www.mikepoweredbydhi.com/products/FEFLOW

M. Rosati, Implementation of a 3d groundwater flow model at the EUREX plant in Saluggia (northern Italy), formerly affected by leakage from the spent fuel pool, 2009 EPRI Groundwater Protection Workshop proceedings, September 15-16, 2009 Charleston, South Carolina, USA.

Sogin S.p.A. (a), Relazione finale sui risultati dell’anno di prove di emungimento dei due pozzi di alimentazione del Nuovo Sistema di Approvvigionamento Idrico, Internal Report (2009).

R. Testoni, R. Levizzari, M. De Salve, Integrated Methodologies for Tracer Use in Radioactive Waste Management, Proceedings of ICAPP 2015 May 03-06, 2015 - Nice (France) Paper 15143.

Sogin S.p.A. (b), Presenza anomala di radionuclidi nella falda superficiale. Azioni eseguite, valutazioni condotte e programmi futuri, Internal report (2009).

http://www.arpa.piemonte.it/

F. Cadini, E. Tosoni, E. Zio, Modeling the release and transport of $^{90}Sr$ radionuclides from a superficial nuclear storage facility, Stoch. Environ. Res. Risk. Assess., DOI 10.1007/s00477-015-1112-7.