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CHLORINE DECAY MODELING IN THE S.GIACOMO STORAGE TANK, NAPOLI

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Abstract: In the last years, the need for drinking water supply has been much increased; therefore, distribution systems are becoming more complex and together tied into interconnected networks in order to transfer water resources between different area services.

Thus, a distribution network may be supplied by some resources, with different source and characteristics, which are mixing in the system; in this situation, water quality control appears to be a particularly relevant topic, which is increasingly studied using mathematical models that simulate transport and transformation phenomena along the various components of the drinking water network, such as the storage tank, which could be considered as a reactor, where water quality could be remarkably modified.

The paper deals with chlorine decay modeling in the S.Giacomo storage tank, one of the most important of the distribution system of Naples. This tank has a volume of 60000 m^3, which is divided into 6 units each one of 10000 m^3; the S.Giacomo storage tank is supplied by two water resources with very different characteristics.

The study has been performed applying a compartment model which predict chlorine concentration variation between inlet and outlet. The model is based on mass balance equation and on continuity equation, which are solved at finite difference with Euler method to yield chlorine concentration along the tank up to the outlet section. The tank has been subdivided into many compartments, but for the comparison data field were available only in inlet and outlet section of the tank.

Furthermore, model equations have taken into consideration the particular inlet conditions, with two inflow pipes.

A comparison between data field and model predictions shows a good fit; mean deviation is, for different initial conditions, in the range of few percent units.

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FOREWORD

Water quality problems have been recognized worldwide from long time as representing a basic topic in drinking water networks management; the needs for an effective protection and monitoring of drinking water has given rise to specific regulations in each country.

Italian regulation on drinking water quality is based on the 236/88 Act, which aknowledges the EU 80/778 Directive; 236/88 Act establishes quality standards and criteria for drinking water using physical, chemical and bacteriological parameters.

Particularly, 236/88 Act considers for each parameter two values, the maximum allowable concentration (MAC), which is a threshold limit, and a guide value (GV), to whom drinking water utilities should address their efforts to improve water quality.

This act fixes sample frequency and analytical methods for sampling and monitoring in the distribution network. However, in many EU countries the tendency to submit EU 80/778 Directive to a revision is growing; in fact, some critical points in the EU 80/778 pertain to the treatment costs, which are related to water sources and are not taken in account in the Directive, and to some parameters, whose CMAs should be updated; moreover, for aesthetical parameters or those which do not affect human health, such as, for example, temperature, conductivity, colour, odour and taste, CMAs should be deleted and substituted by GVs.

In 1994, the organization of water utilities has been changed by the 36/94 Act, which has the main goal to group different management authorities of drinking water, sewerage and treatment plant into one management structure in the view of complete water cycle; thus, this act, when completely applied, will be of relevant consequence on water management in Italy, where, in the last years, the need for drinking water supply has been much increased; therefore, distribution systems are becoming more complex and together tied into interconnected networks in order to transfer water resources among different area services. Thus, a distribution network may be supplied by some resources, with different source and characteristics, which are mixing in the system; in this situation, water quality control appears to be a particularly relevant topic, which is increasingly studied using mathematical models that simulate transport and transformation phenomena along the various components of the drinking water network (Clark et al., 1988; Grayman et al., 1988; Clark, 1994); these models could be divided into two broad groups, steady-state and dynamic ones.

A particular component, which has been only recently taken into consideration in water quality studies is the storage tank, which should be considered as a reactor, where water quality could be remarkably modified (Mau et al., 1995; Clark et al., 1996).

This paper deals with chlorine residual decay modeling in the S.Giacomo storage tank, one of the most important of the distribution system of Naples.

The study has been performed applying two modeling approaches, which predict chlorine residual concentration first-order decay constant in the tank; the first one is a compartment model, which is based on mass balance equation and on continuity equation; in these equations, the particular inlet conditions, with two inflow pipes, has been taken into consideration. The second one follows simple lagrangian approach of water volume moving with the flow field.

CASE STUDY PRESENTATION. S.GIACOMO STORAGE TANK

Drinking water supply network of Naples is quite complex and peculiar due to the irregular orographical configuration of the town, which is placed from 0 to over 400 meters on the mean sea level (m.s.l.). Thus, network uses many storage tanks, which are set on different altitudes, depending on the supplied areas.

The S.Giacomo storage reservoir is one of the most relevant tanks of Naples water supply network; its water level is 230 meters (msl). It provides drinking water to a large area of Naples, which is placed from 130 to 190 m.s.l. .

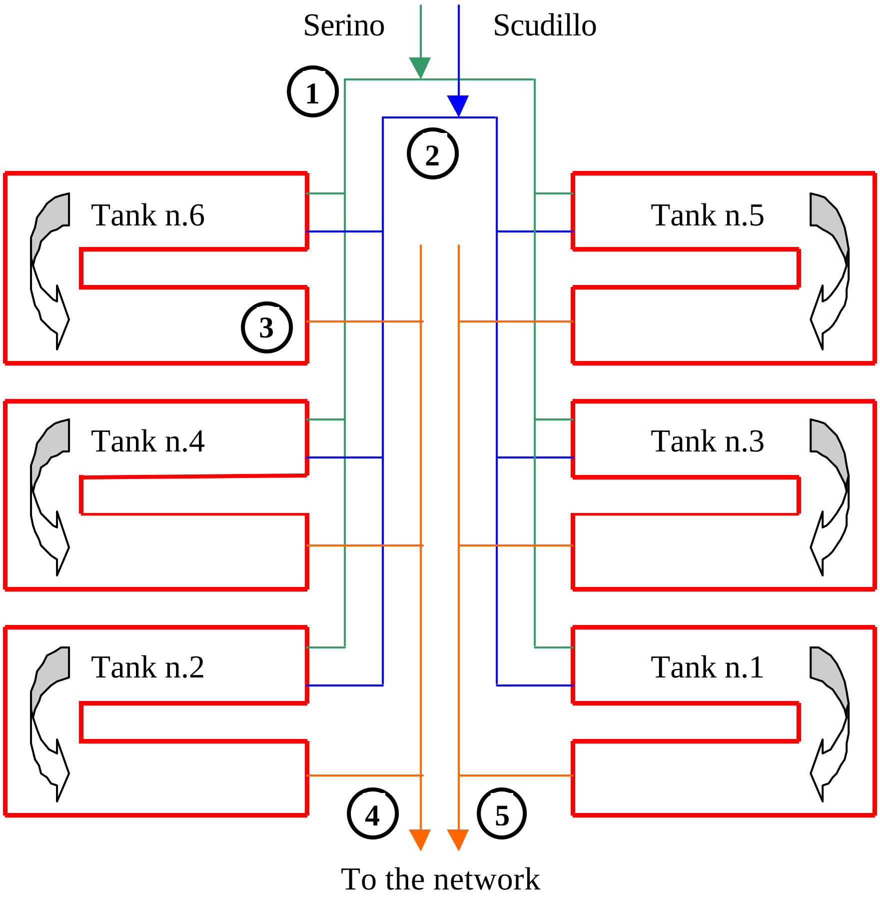


Fig.1 – S.Giacomo reservoir hydraulic scheme

The reservoir is placed in a tunnel and holds roughly 60000 m³, when full; this volume is divided in 6 tanks and each one contains 10000 m³. These tanks have a simmetric configuration with respect to feeding scheme, with 3 tanks on each side of the feeding pipelines; furthermore, the position of outcoming pipelines towards the network, which are made in cast iron and have a 700 mm diameter, is simmetric too (Fig.1). It should be noted that each tanks has another outlet pipeline, which has a 400 mm diameter and is used to feed, using a pumping station, another storage tank, called Cangiani, with water level of 303 meters (slm).

Each tank has a polycentric transverse section with a concrete liner; length and width are, respectively 135 m and 22 m, while water height is of 5.5 m. Polycentric cross section could be approximated to a rectangular one 5.5 m × 6.6 m.

In the first step of the study, before the application of the model, it seemed to be advisable to characterize, together with inflow water quality, the mixing regimes in the reservoir; in fact, the S.Giacomo reservoir has two inflows; they are very different for flowrate and water quality, so that incomplete mixing conditions could affect reservoir compartment idealization to be assumed in model application.

Particularly, the first inflow comes, using a 1000 mm diameter steel pipeline, from a static head called Cancello-Serino. The second inflow comes, using a 1300 mm diameter teel pipeline, from the pumping station called Scudillo, which lifts the water from the downstanding Scudillo reservoir. This station has 11 pumps, for a maximum overall flowrate of 3600 l/s. The medium whole inflow incoming into the S.Giacomo reservoir is of almost 1300 l/s.

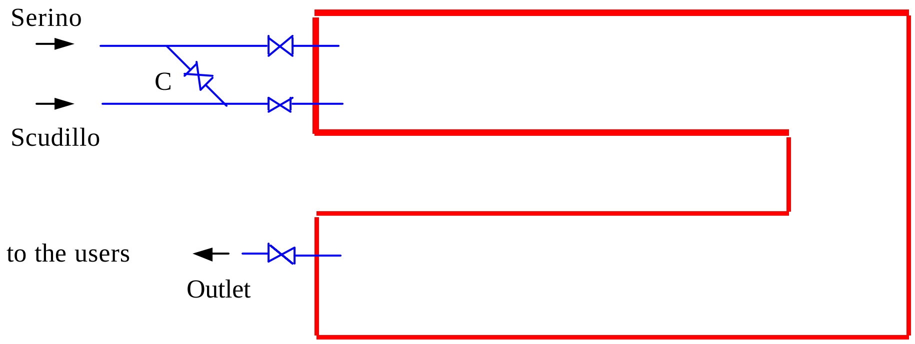


Fig.2 - S.Giacomo reservoir inlet/outlet scheme for each tank

Furthermore, in the S.Giacomo feeding scheme, each inflow has its own separate adduction line to share the flowrate into each tank; thus, each inflow has its own inlet pipe; therefore, inflows mixing is in the tank. However, there is an on/off valve C, which links the inlet pipelines. Thus, it is possible to shift the Serino inflow into the Scudillo one so that inflows mixing is in the inlet pipeline (premixing) (Fig.2).

Finally, it should be also noted that inlet pipes arrive to the tank with different levels; the Serino inlet, which has a diameter of 400 mm, is above the tank free surface, the Scudillo one, which has a diameter of 600 mm, is near the bottom, at a depth of about 4 m from the surface water (Fig.3). Furthermore, the inlet pipelines have not the same diameter and so, due also to the different flowrate values, inlet velocity are different; therefore, another critical point to investigate was the influence of this positions on water quality.

The study started with the inflows characterization using 6 parameters, such as temperature, pH, electric conductivity, calcium ions concentration and Fe and Mn concentrations. The samples were collected at points ① and ② (Fig.1) along the period of 1 day to point out daily variations. Preliminary results showed that Fe and Mn concentration values were negligible; thus, these parameters were no more considered.

For temperature measurement, a mercury thermometer was used, while standard electrode method was applied for pH. Conductivity, with is related to ions concentration in the water, was measured using a conductivity cell with a KCl standard solution, while for Ca^{++} ions measurement EDTA titration method was applied. Table n.1 shows means μ and standard deviations σ along 24 hours of the 4 considered water quality parameters as well as the water flowrate, for the two inflows. The Table suggests some comments.

Table 1 - Water flowrate/quality parameters for Serino and Scudillo inflows

Inflow	Flowrate	Temperature	PH	Electric conductivity	Ca^{++} Ions
	L/s	°C	---	μS/cm	Mg/L
Serino - μ	304.16	11.58	7.93	373.88	68.66
Serino - σ		0.68	0.10	3.9283	0.9428
Scudillo - μ	959.2	13.22	7.08	644.44	100.33
Scudillo - σ		0.42	0.41	10.6574	0.4714

The flowrate mean ratio Serino/Scudillo is 0.317; the temperature is quite constant and is lower for the Serino. The pH is slighty basic for the Serino and near neutral for Scudillo. Finally, the Serino electric conductivity and Ca^{++} ions concentration are, respectively, 58% and 68% with respect to the Scudillo ones; thus, Serino water has lower specific weight than Scudillo one.

All the parameters in Table 1 show a very little daily variability; thus steady-state assumption appears to be reasonable.

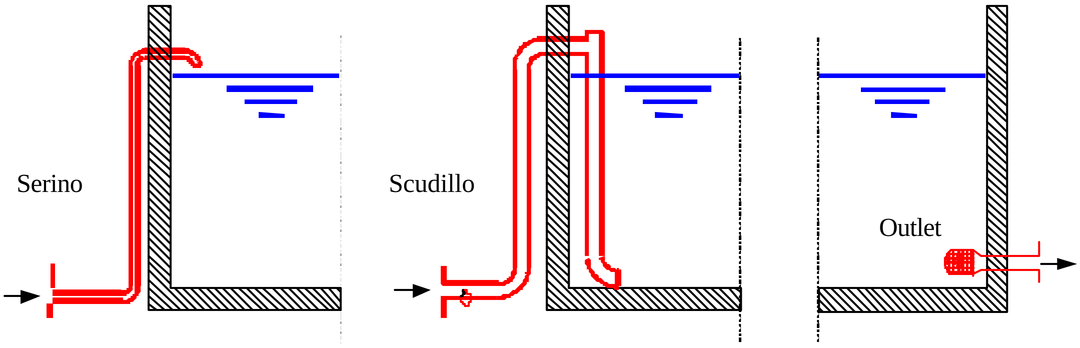


Fig.3 - S.Giacomo reservoir inlets/outlet position for each tank

Furthermore, flowrate measurements has shown that the whole inflow divides in equal parts between the two sides of the reservoir, with a mean difference of about 3%; thus, the study was addressed to one side, i.e. 3 tanks only, and, particularly, to the tank n.6 (Fig.1). Therefore, together with inflows water quality characterization, samples were collected in the tank n.6 to point out, as previously outlined, inflows mixing conditions in this tank. Thus, the samples were collected on the inlets, on the outlet and, inside the tank, at the starting section and at the final section, on the surface water, at 1/2/3/4 m below the water surface and at the bottom, i.e. at 5.5 m below the water surface; for in-tank sampling a pump with a concrete ballast linked with a graduated pipeline was used. Conductivity and Ca^{++} ions concentration were used as indicators.

The results have shown that there is not significative layers formation in the tank due to the different water quality characteristics and to the particular inlet position. Figg.4a/4b show daily mean conductivity distribution for different depths at the starting section and at the final section of the tank n.6.

Fig.4a - Tank n.6. Conductivity at starting section

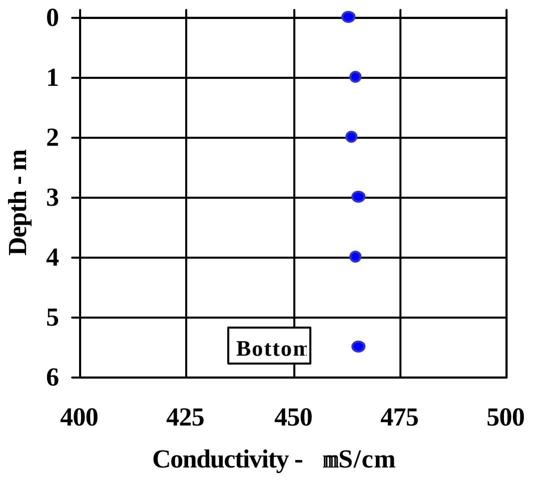
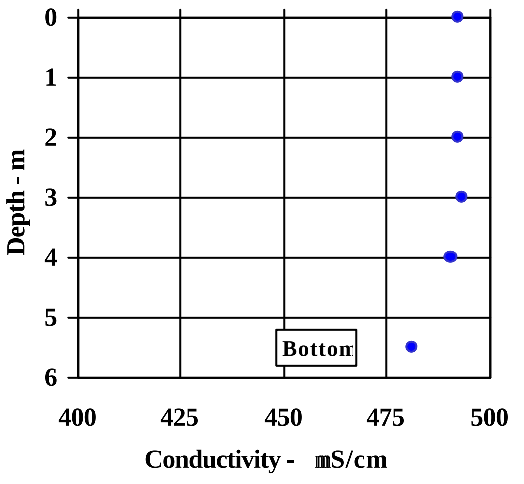


Fig.4b - Tank n.6. Conductivity at final section



MODEL PRESENTATION AND APPLICATION

The study has been performed with the general aim to point out and model change in chlorine residual concentration due to retention time into the tank; then, in modeling effort, first-order kinetic was assumed for chlorine decay process.

Two modeling approaches, which predict chlorine residual concentration first-order decay constant k, were applied and compared; the first one is a compartment model, which is based on mass balance equation and on continuity equation (Clark et al., 1996); in these equations, the particular inlet conditions, with two inflow pipes, has been taken into consideration. The equations are solved at finite difference to yield chlorine concentration decay constant in the tank.

The second one follows the lagrangian approach of water volume moving with the flow field in order to estimate decay rate and, thus, provides as well decay constant k.

As formerly outlined, no layer formation has been observed in the the tank n.6; thus, in first model application only one compartment, which is idealized as well-mixed reactor, was considered; however, model equations has been adapted to take into consideration the particular inlet conditions, with two inflow pipes (Fig.5).

The approaches were applied to estimate first-order decay constant k for chlorine residual in the tank; particularly, for models application purpose, samples were collected from 8.00 A.M to 5 P.M. on the two inflow pipelines, i.e. Serino and Scudillo ones, at points ① and ② (Fig.1), on the outflow pipeline of tank n.6 at point ③ in Fig.1 and on the two pipelines leaving from the reservoir to the Naples network at points ④ and ⑤ in Fig.1; tha data are shown in Table n.3. For chlorine residual measurement ortho tolidine method was applied.

Table 3 – Chlorine values observed from 8.00 A.M to 5 P.M. – mg/L

Points of measurement	Chlorine – mg/L	
	µ	σ
Serino – point ①	0.175	0.025
Scudillo – point ②	0.1875	0.02165
Theorical mixing	0.185	0.0206
Tank n.6 outflow – point ③	0.1125	0.0216
Outcoming pipeline – point ④	0.1125	0.0216
Outcoming pipeline – point ⑤	0.1125	0.0216

As flowrate measurements showed that hydraulic symmetry assumption is well suited, tank inflows and outflow are obtained as part of whole measured flowrates, i.e. 1/6.

If Q_1 and Q_2 are the incoming flowrates, Q_{out} is the outflow and V is water volume of the tank, compartment model equations are:

$$\frac{dV}{dt} = \left(Q_1 + Q_2 - Q_{out}\right) = (Q_{in} - Q_{out}) \qquad (1a)$$

$$\frac{d\left(C_{tank}\, V\right)}{dt} = Q_1\, C_1 + Q_2\, C_2 + \; Q_{out}\, C_{tank} - k\, C_{tank} = Q_{in}\, C_{in} - \; Q_{out}\, C_{tank} - k\, C_{tank} \quad (1b)$$

where k is first-order decay constant, C_{tank} is chlorine concentration in the tank and C_{in} could be obtained by a mass balance as:

$$C_{in} = \frac{C_1\, Q_1 + C_2\, Q_2}{Q_1 + Q_2} \qquad (2)$$

where C_1 and C_2 are inflows chlorine concentrations. After some appropriate adjustements, substituting (1a) into (1b), eq. (1b) yields:

$$\frac{dC_{tank}}{dt} = \frac{Q_{in}\left(C_{in} - C_{tank}\right)}{V} - \; k\, C_{tank} \qquad (3b)$$

Eq.(1a) expresses tank volume change due to difference between inflows and outflow, while eq.(1b) represents chlorine time changing into the tank. At finite differences Eq.(3b) yields:

$$\frac{\Delta C_{tank}}{\Delta t} = \frac{Q_{in}\left(C_{in} - C_{tank}\right)}{V} \text{-}\, k\, C_{tank} \qquad (4b)$$

where k is the unknow to be defined as:

$$k = \left(\frac{Q_{in}\, C_{in}}{V} - \frac{Q_{in}\, C_{tank}}{V} - \frac{\Delta C_{tank}}{\Delta t} \right) \frac{1}{C_{tank}} = \frac{Q_{in}\, C_{in}}{V\, C_{tank}} - \frac{Q_{in}}{V} - \frac{\Delta C_{tank}}{C_{tank}\, \Delta t} \qquad (5b)$$

In eq. (5b), in order to define k, the mean of each terms from 8.00 A.M. to 5.00 A.M. was taken in consideration.

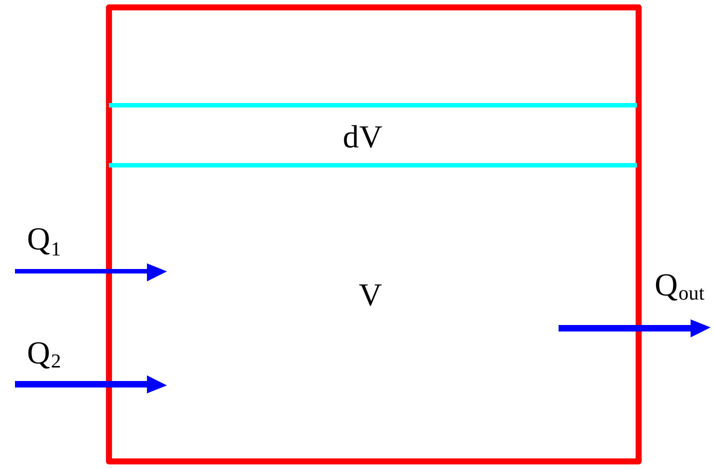


Fig.5 – Compartment model for S.Giacomo tank n.6

On the contrary, Lagrangian approach follows a water volume as it moves with the flow along the tank; thus, change in chlorine concentration could be estimated for first.-order decay model as:

$$\frac{dC_{tank}}{dt} = -k\, C_{tank} \qquad (6)$$

which can be integrated by separation of variables to yield:

$$\ln C_{out} - \ln C_{in} = -k\, t \qquad (7)$$

Taking the exponential of both sides gives:

$$C_{out} = C_{in} e^{-kt} \qquad (8)$$

where C_{in} is inflow chlorine concentration 8.00 A.M., which is the starting time t=0, and C_{out} is outflow chlorine concentration at final time $t{+}RT_{t=8.00\ A.M.}$, where $RT_{t=8.00\ A.M.}$ is the retention time into the tank starting from 8.00 A.M. . Thus, in lagrangian approach $RT_{t=8.00\ A.M.}$ must be estimated to solve (8); if $\overline{Q}_{out}$ is the mean outflow in the tank from 8.00 A.M. to 6 P.M. and V_0 is water volume in the tank at time t=0=8.00 A.M., $RT_{t=8.00\ A.M.}$ in the tank could be estimated as:

$$RT_{t=8.00A.M.} = \frac{\overline{Q}_{out}}{V_0} \qquad (9)$$

From (9), using a successive approximations method, $RT_{t=8.00\ A.M.}$ was estimated as 9 hours and 54 minutes, so that C_{out} is the outflow chlorine concentration at 6.00 P.M. . It should be pointed out that the $RT_{t=8.00\ A.M.}$ calculated for lagrangian approach is very similar to the time step, from 8.00 A.M. to 5 P.M., considered in samples collection for compartment model, so that the two values of k, i.e.compartment model and lagrangian model, can be better compared. Table n.4 shows chlorine residual concentration values used in lagrangian approach.

Table 4 – Chlorine residual concentration values used in lagrangian approach

C_{in}	C_{out}
mg/L	mg/L
0.200	0.100

Models results are shown in Table n.5; the two approaches applied show a difference, with respect to their mean value, in k estimated value of almost 8%, which could be considered acceptable taking in account the simplified assumptions. This value could be useful in drinking water networks management context.

Table 5 – Comparison between model results

Approach	K	ε	ε
	1/day	1/day	%
Compartment	1.547		
		0.132	8.21
Lagrangian	1.679		
Mean	1.613		

CONCLUSIONS

Water quality modeling and control is an emerging field in drinking water supply management; the need to respect more strict and safe drinking water quality standards requires a clear and effective knowledge of transport and transformation phenomena occurring in water supply networks, which could affect final quality levels.

Under this regard, some attention should be payed to the tank, which could be considered as a reactor. In this paper water quality in the S.Giacomo storage reservoir (Napoli) has been characterized; this reservoir has two different inflows; their mixing has been investigated and no stratification were observed. Furthermore, change in chlorine residual concentration due to tank detention has been assessed using two different approaches, a compartment model and a lagrangian model. These approaches were applie to estimate chlorine residual first-order decay constant; preliminary results show a good fit between two models predictions.

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Furthermore, outflows characteristics were analyzed; each side of the reservoir, i.e. 3 tanks, has its own outcoming line to the network; comparison was carried out between theorical mixing values and observed values in the 2 outcoming pipelines. These values are always lower than the former, due to different Serino/Scudillo ratio in each tank, and show higher variability (Table n.2). It should be noted that the samples for theorical mixing values were collected at points ① and ② (Fig.1), while the observed values in Table n.2 are the means of samples collected at points ④ and ⑤ (Fig.1).

Table 2 – Theorical mixing value and observed values

Outflows	Electric conductivity - µS/cm		Ca^{++} Ions – mg/L	
	Mean	Stand. Dev.	Mean	Stand. Dev.
Theorical mixing	577	15.7	91	0.81
Observed values	492	29	81.6	2.65