SOLUTIONS TO DRAINAGE PROBLEMS IN URBAN AREAS

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Indice

1 ABSTRACT

A failure in drainage system can induce in urban areas frequent inundations of underground floors or extension of local damps. It can be observed other more dangerous events as:

- Groundwater fluctuations (rise and decrease in short and medium time due to heavy rain, economical and social changing, civil and industrial variation of withdrawals, seasonal variation of irrigation).
- Subsidence
- Salt water wedge shape aquifer during pumping test closer to coastal area
- Hydrogeological instability nearby river bank with an increasing deterioration of water quality (piping and subterranean erosion or stagnation point that could make drainage system not functional.

These environmental problems are caused by uncontrolled development of some anthropogenic factors: heavy withdrawals during time, seepage irrigation. Much of the surface of urban areas is impermeable due to roads, buildings and surface coverings. Because of this covering, the recharge is reduced and the direct runoff has increased.
These problems could occur both in Italy and in the world; with different problems and hydrogeological settings, different drainage systems are designed; In Romania, e.g. Galati city (ZAMFIRESCU F., 2003), an increasing groundwater level caused by a loss of industrial and civil system water during the last 20 years is within 5 meters. The problem could be solved with an horizontal drainage system pumping well useful for the low hydraulic conductivity and anisotropy vertical settings. A similar example is Kuwait City (MUHAMMAD F., 2001) where the proposed solution is given by a vertical and horizontal wells system for having about 2 meters drawdown.
Further interesting situation are observed in Italy; least but not last it is better remind the case of Buenos Aires City (FINOTTI R., 2007)where a salt water encroachment is caused by a coastal water pumping system. The problem solution could be a better management of withdrawals. In London an increasing rate of about 1 meter per year is due to a heavy de-industrialization process.
In Milan which is one of the most city where the drainage system is required, there are both a piezometric rise level and an unsuitable water flow net (BERETTA ET ALII, 2006).

2 A FORECASTING MODEL: THE STUDY CASE OF MILAN

Previous examples are useful for a better comprehension of the problem in many cities which are subjected to piezometric changes of several meters per year. From the fact that the groundwater oscillations cause many hardship for buildings and foundations, a forecasting instrument is necessary for a quickly not expensive intervention. This kind of activity can consist of:

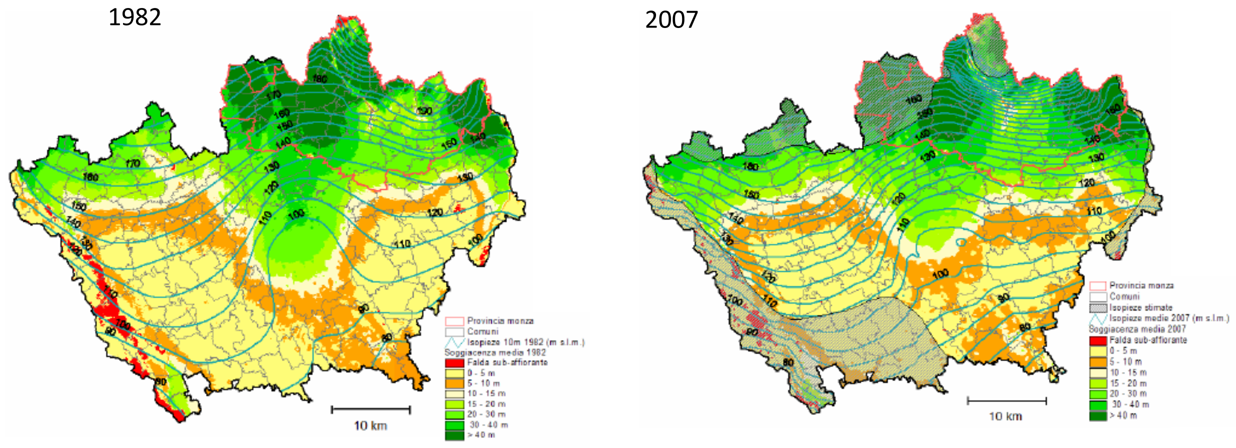

Figure 1 - Piezometric variation level during 1982-2007

- Historical study of factors that influenced piezometric variation and groundwater behavior i.e. the hydrogeological balance factors (Figure 1).
- Groundwater behavior modeling based on identification of hydrogeological parameters in the study area and testing it for times
- A detailed forecasting behavior of groundwater during heavy rain period and pumping variation. This is possible to make a choice for a better drainage design.

Moreover, it can be done a forecasting example in Milan hinterland.

3 STUDY OF WATER BALANCE FACTORS

3.1 STUDY OF GROUNDWATER HEAD COMPARED WITH RAINFALLS AND WELLS WITHDRAWALS

The data set available has to be massive, and including number of years, both the withdrawals of the civil and industrial wells and of rainfall events. While a correct evaluation of connection between factors can be carried out only with the support of mathematical models, a first qualitative approach can be useful; e.g. Figure 2 demonstrates that the groundwater head rise is inversely proportional to withdrawals decrease. The velocity of groundwater head increase is of 16 m within 20 years, and its trend is approximately as linear as the velocity of withdrawals decrease, which is about 8 millions of m^3 within 20 years .

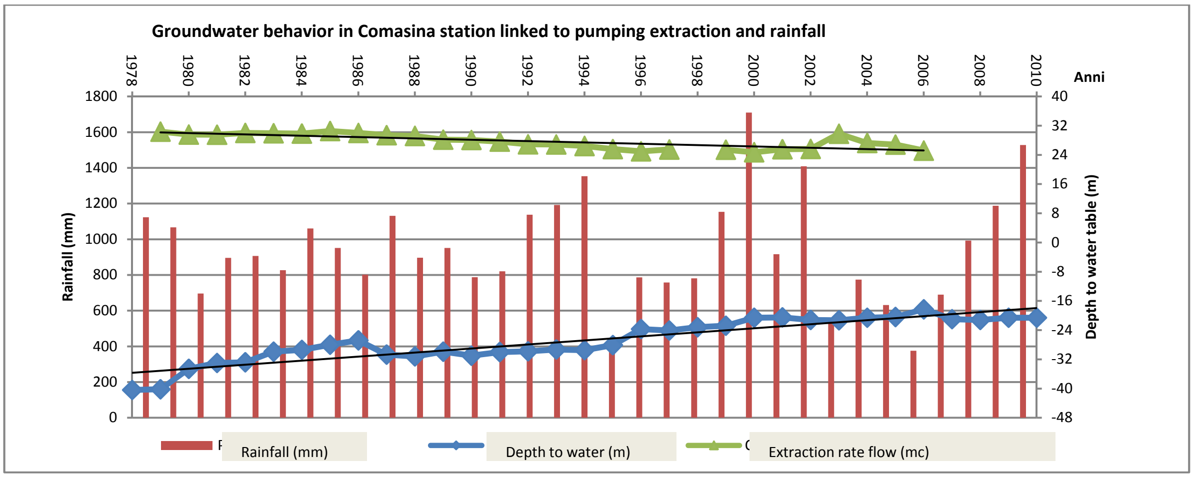

Figure 2 - Time series analysis

For this reason, the functions describing this behavior have been represented in Figure 2 by two right lines. The contribute of the rainfall is also recognizable in the Figure 2, where it can observe an increase of 2-3 m over the line of medium groundwater head rise through the time , when the annual rainfall are exceeding 1000 mm. This first step allows to a good knowledge of essential features of the problem.

3.2 MATHEMATICAL MODEL

After the first approach, a mathematical model must be developed on the basis of collected data; so by means of hydrological analysis of at least last 50 years, can be evaluated evapotranspiration, runoff, aquifer recharge due to rainfall and to irrigation, while the hydrogeological analysis of pumping test provides the data on hydrogeological parameters.

The hydrogeological balance based on a mathematical model could give a development in a long term with a reasonable forecasting of pumping and of rain variable hypothesis.

These forecasting can give a dimension of an interval of confidence where the pumping well must work for maintain the groundwater level under the critical threshold.

However any longtime economic recession or growth are not easily forecasted and the related changes of groundwater levels, as resulting from the calculations, can't be verified.

For these reasons the application of this kind of forecasting has to be done usually in a short period (three or five years) . During a so small interval time, water abstraction and rain are collocated in an interval with values based on available data.

3.3 SHORT TIME PROBABILISTIC ANALYSIS

Therefore probabilistic analysis is suitable only for this short time interval. The probability curves are obtained with a Monte Carlo approach by extrapolating sample from Gaussian distribution limited into max and min observed values. These kind of curves could give an information about piezometric level overcoming.

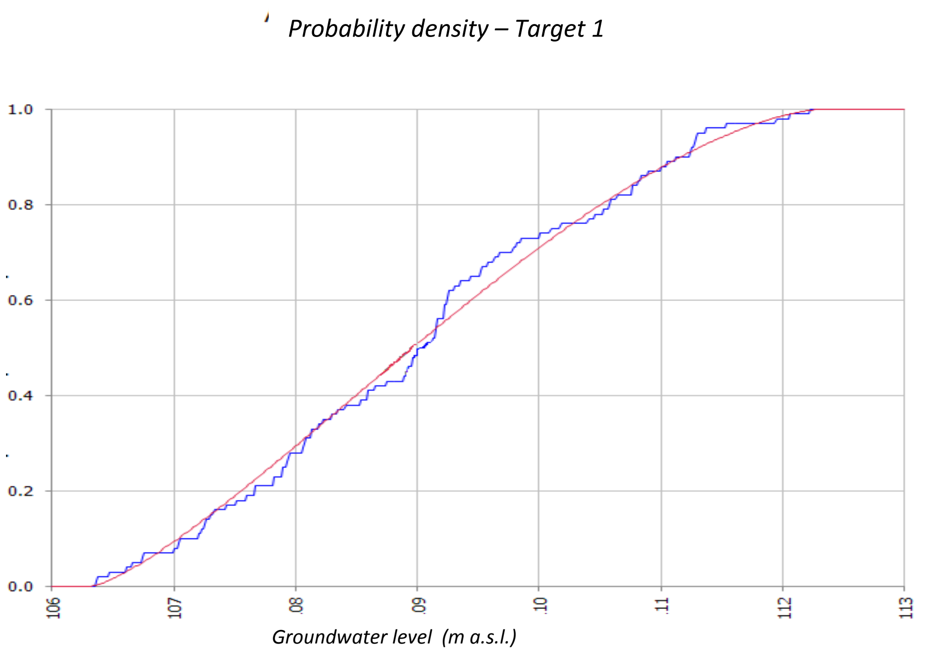

Figure 3 - Probabilistic analysis

These preliminary remarks highlight that it is needed at first acquire an overall knowledge of the factors controlling the changes of piezometric head. The mathematical model can improve these constraints , particularly the quantitative aspects, but the main role is played by the correct choice of the critical head (Figure 3).

The critical head must be correctly decided by means of short time forecasting, because the socioeconomic factors (which have a marked volatility) play an important role in producing the changes of piezometric levels, which are strongly related to industrial and drinking water wells withdrawals .

4 SURFACE DRAINAGE

Surface drainage in a few depth meters needs to follow study:

- Hydrogeological settings and monitoring of studied area
- A study of river boundary-groundwater flow connection, even with 3D reconstruction (isopiezometric/equipotential)
- Monitoring flownet for all studied aquifer

A detailed piezometric surface and geological setting in the study area with an identification of aquifer, their thickness and rainfall response.

4.1 A DEVELOPMENT OF “WORST CASE”

The worst case is useful to avoid a lack of intervention instruments for not forecasting geological events based on significant data. The drainage induced by the trench involves both the aquifer and reduces their piezometric level enough to not interest only the drainage bottom.

The aquifers are one confined, whose depth is deeper and another unconfined. For this reason, the design has been made on two levels, including drainage systems in a excavated trench till 5 meters in depth; moreover, a wells system is added for having a better catchment of confined aquifer.

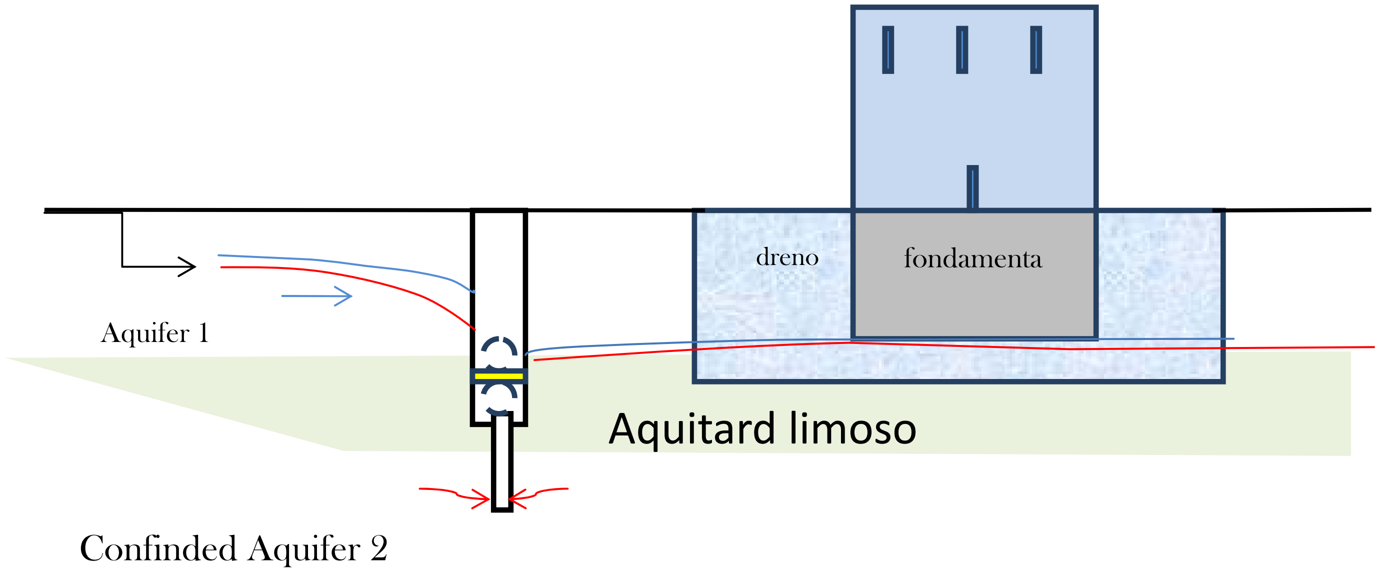

Figure 4 - Two levels system drainage

When an independent design system of depth is required, an horizontal drainage system (as a drainage gallery) is designed.

When the depth of the aquifer is over 5 m, an horizontal drainage system (as a drainage gallery) is more suitable than the trench .

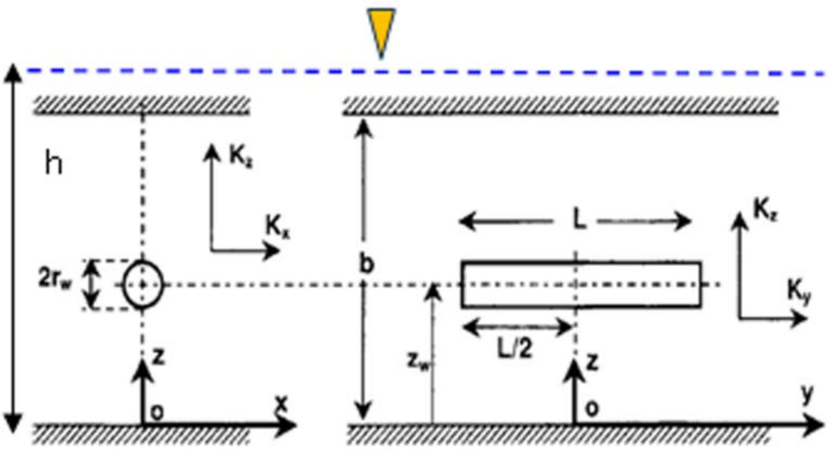

Figure 5 - Horizontal well drainage

In fact, the gallery is more efficient in depth and can make a strong drainage action. An inclined horizontal drainage system is designed in order to extract a flow rate Q which can cause the wanted drawdown at a x distance. In order to compute the rate of extracted water and the drawdown, the GOODE AT AL. (1987) relationship can be used

$$s = \frac{Q}{2\pi T} ln\left(\frac{1.5\sqrt{\frac{Tt}{S}}}{x} \right) + \frac{Q}{2\pi LK}(\sigma_z + \sigma) \quad \textbf{(1)}$$

With Q (m3/s) = flow rate of drainage gallery, T (m2/s)=aquifer trasmissivity, S= storage coefficient, σ (-)=skin factor of well depending on radius well R (m), thickness confined aquifer (m), location of drainage respect to the bedrock h_w, σ_z (-)= factor dependent on thickness b (m), drainage location and hydraulic conductivity, L(m) = drainage gallery length.

If there Is also a river boundary that can induce some piezometric water table oscillations, it is necessary to take in account of its with PINDER AND COOPER relation (1969):

$$h_p = \sum_{m=1}^{p} \Delta H_m \left\{ erfc \frac{u}{2\sqrt{p-m}} \right\} \qquad (2)$$

Where $h_p(m)$= piezometric levels at a x distance from the river, $\Delta H_m(m)$= rising at the time interval m, p (-)= time interval number, m(.)=integer number, u(-) factor dependent on distance x, storage coefficient and Trasmissivity (m ^{2}/s).

The groundwater head must be controlled in order to avoid both inundation of infrastructures and suffusion or subterranean erosion. This last phenomena is induced by anomalous seepage velocity, occurring when piezometric gradient overtakes a critical value.

The piezometric gradient J depends on groundwater head (and therefore on gallery discharge) as follows (COLOMBO ET ALII, 2011):

$$J_i(K,S) = \frac{H_{i+1} - H_i + H_i erf(u_i)}{x} = \frac{\Delta H + H_i erf(u_i)}{x} \qquad (3)$$

Then it is possible to forecast the right extraction flow rate Q, well-known hydrogeological parameters and river fluctuation (COLOMBO ET ALII, 2012):

$$Q(t) = 2\pi K \frac{s(x,t)}{\left(\frac{1}{b} + \Lambda\right) \ln\left(\frac{x'}{x}\right)} \qquad (4)$$

The most suitable drain distance from river boundary can be evaluated using a computation or a series of graphics (Figure 6), which prove that the more the gallery approaches to the river the more the specific discharge increases. A similar behavior can be found moving the drain upward closer and closer to river.

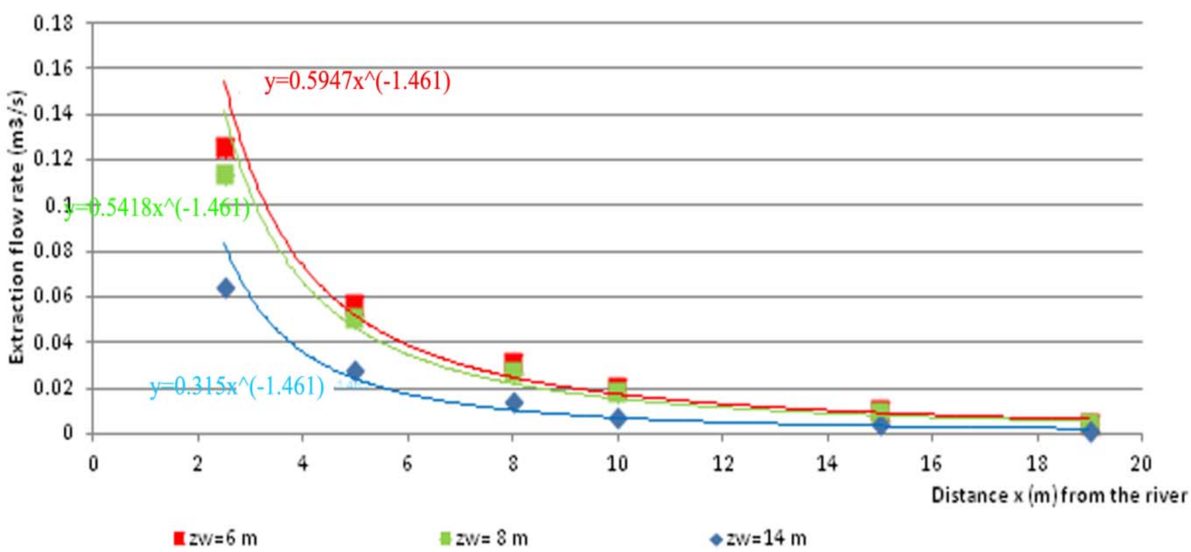

Figure 6 - Flow rate dependent on distance x from river and from bedrock

5 VERTICAL DRAINAGE

The wells are commonly employed in order to drain the deeper section of the aquifer, and allow to have a good control of the piezometric depression and of the flow rate, with or without the draining trenches.

The wells design must take in account of :

- Operating optimal flow rate without overcoming critical condition
- Filter obstruction

- Hydro-chemical analysis in order to avoid filter incrustation

The Knowledge of the well design is good and it can be highlighted only that the wells design must consider the location of the working area, overall if the piezometric depression includes:

- Coasy
- Suburbs of the city
- Town

5.1 COASTAL AREAS

Many coastal cities as Buenos Aires have a problem due to the fact that, when it is necessary to lower the water table, withdrawals of drainage wells can generate the salt water wedge shape aquifer and therefore a decay of drinking water quality.

The head changes due to water extraction in these conditions are very remarkable.

Therefore the drainage design must consider carefully any factor influencing the head changes, e.g not only the heterogeneities of hydrogeological setting, but also a different density at various depth in aquifer.

For this reason the head directly measured in piezometers screened at different depth cannot be compared to, as the fact that piezometric head and density of water are correlated inversely. Referring the measured piezometric level to freshwater equivalent head could be a good solution.

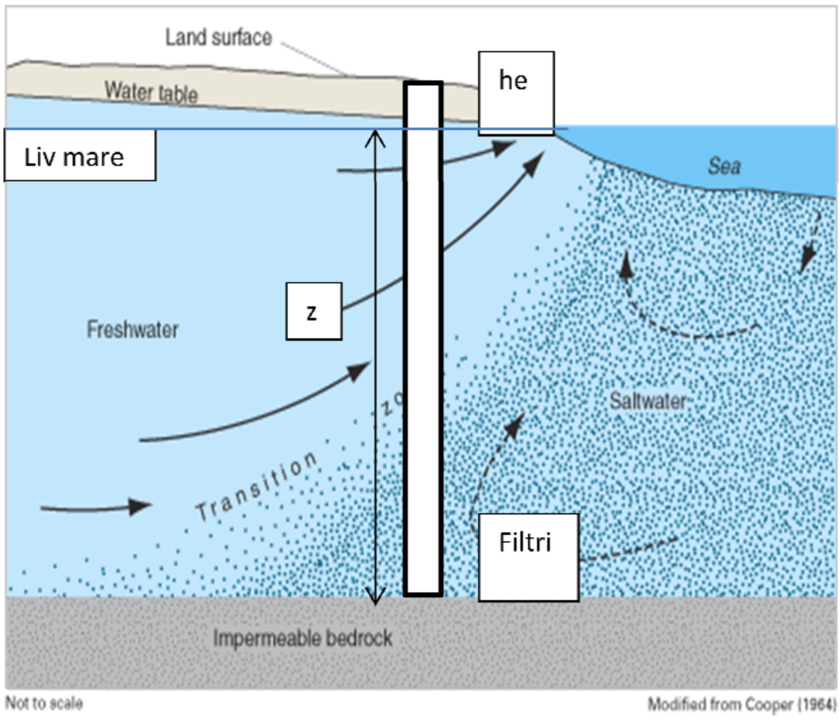

Figure 7 - A salt water wedge shape aquifer (from Cooper, 1964)

The processing, represented in the next formulation, allows to uniform all the different density levels in one of only freshwater

$$h_e = h_s * \left(\frac{\rho_s}{\rho_f}\right) - z * \left(\frac{\rho_s}{\rho_f}\right) + z \quad \textbf{(5)}$$

It is possible to obtain with correct values:

- piezometric surface which shows the real water flow towards coast
- Dupuit relation application for obtain drawdown

With the same flow rate drawdown and the capture curve are bigger for superficial wells over the interface. This is due to drawdown trasmissivity dependence. The trasmissivity is dependent on filters length as shown in Logan's formulation:

$$T = 2Q * (L_s * s * w) \quad \textbf{(6)}$$

The shallow wells efficacy is improved by the fact that deeper wells can generate the upconing of salt water.

5.2 SUBURBAN AREA DRAINAGE

Where the piezometric depression generated by the pumping wells are each other distant, the natural equilibrium is easy reached, and drainage by means of several wells can take place without induce environmental problems. These conditions are mostly found in suburban areas, where the adequate piezometric lowering can be achieved by extracting remarkable flow rates.

Thus, can be suggested that the wells design follows these steps:

- Hydraulic test as slug test for measure aquifer hydraulic conductivity (m/s) and the optimal well depth
- Operating flow rate and filtered zones: it must consider critical flow rate computed usually with Sichardt relationship. Filtered zones are put from topographic surface to 20 depth meters.
- Distance wells: it depends on available space (it is less and less in heavy urbanized areas) and on drawdown caused by pumping well. E.g. it is about 24 meters.

It is evaluated the impact on superficial boundary nearby the well drainage system.
The number, the location and the extracted flow rate depend on the drawdown and the intervention area.

5.3 URBAN AREAS

In urban area a superposition of piezometric depression due to nearby wells system can occur. In fact, along piezometric watershed some low velocity zone or stagnation points are formed. The flow lines are always curvilinear and they follow very lower piezometric gradients with a waterlogging. A creation of unfavourable zones for drainage system can be formed (MARY P. ANDRSEN, 1992). Stagnation points can be an higher piezometric level when an high seepage occurs in an area enclosed by piezometric depression. These points are defined as zones where the flow is quite zero and the forces on that point are equal to all directions (STRACK, 1989; SHAN, 1999; CHRIST ET ALII, 2002; CHRIST ET ALII, 2004).

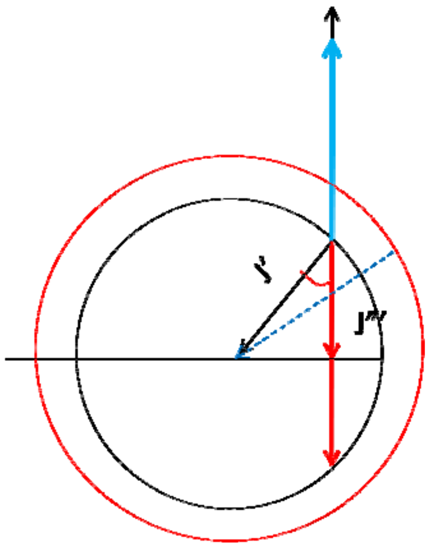

Fig. 8 - Formation of a stagnation point in an inclined groundwater with uniform velocity U

Along the simmetric axis the y coordinate of stagnation points is

$$y = w + \frac{Q \ln \frac{x}{r}}{\pi T} - 2Jx \sin\beta \quad \textbf{(7.1)}$$

$$y' = \frac{Q}{x\pi T} - 2J \sin\beta \quad \textbf{(7.2)}$$

The derivative of Y equal to 0, is possible only when

$$\frac{d^2}{\cos^2\beta} = \frac{R_0^2}{\sin^2\beta} \Rightarrow \frac{R_0}{d} = \tan\beta \quad \textbf{(8)}$$

An example where β is obtained with numerical model and analytical one, can show a linear behavior with a correlation similar to 1.

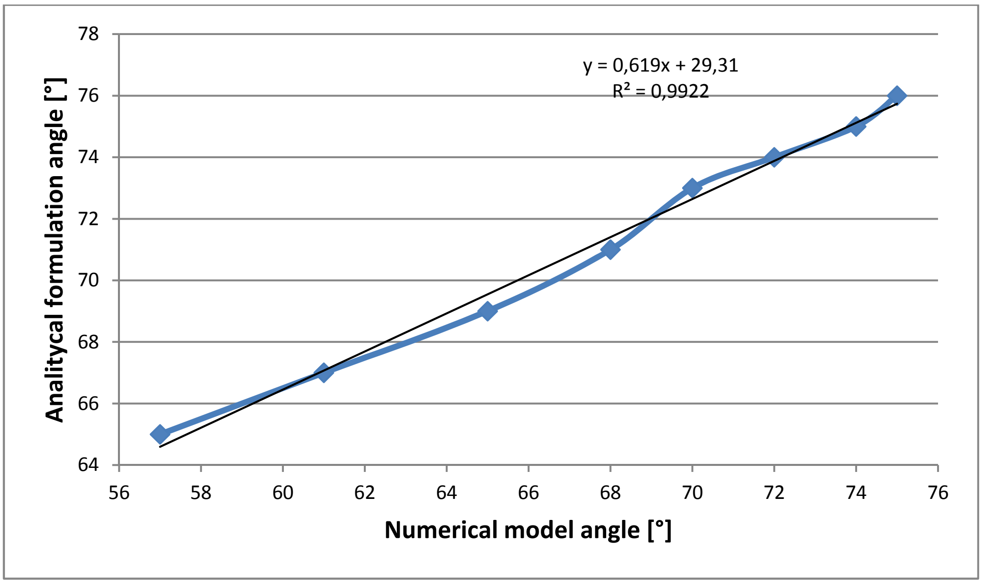

Fig. 9 - A correlation between analytical and numerical model

6 CONCLUSION

The drainage effect in urbanized area is a problem not easy to solve as it is presented in this note; many problems are observed in the world: groundwater oscillations due to seepage or pumping variation, salt water wedge shape aquifer.

It is important to have a forecasting capacity in order to know when a drainage systems must work with a specific flow rate extraction. Without a correctly designed drainage system, the groundwater rise can cause many hardship for infrastructures and buildings.
A forecasting model must consider firstly these activities:

- Historical series analysis of time variables (rainfall for at least 50 years, irrigation due to agricultural working, civil and industrial extraction well during at least 50 years);
  this can induce a creation of workers for a monitoring of extreme events.
- The identification of overcoming critical water table value where the drainage system must work with the specific flow rate extraction
- Probabilistic analysis with a percentage of overcoming critical level

A forecasting model must consider also a "worst case" as:

- Correlation between rainfall and groundwater oscillations
- Statistical analysis in order to have a return period of the worst rainfall event correlated to worst groundwater rising

The designing interventions must consider also a realization of interception drain and net water evacuation channel.

Drainage systems designing in urbanized area must take in account different boundary condition as :

- *Salt water wedge shape aquifer and sea boundary e.g Buenos Aires*
- *Hydrometric oscillations and river boundary e.g Milan, Lambro river*
- *Stagnation areas in urban zone e.g. Milan*

The problem of drainage system can be solved with an integrated drainage and monitoring systems for different areas, representing the prevailing boundary conditions studied in this note. Before the designing systems, a comprehensive field investigations and pumping tests must be performed to assess the hydrogeological parameters.

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