Impact of water table variations on sewer networks

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Abstract: Prediction of useful life of sewer networks is essential for the management of urban area. When one or several groundwaters are located in a terrain containing a sewer network, fluctuations of water table generate pressure variations and harmful physico-chemical weathering conditions for the network and its surrounding area. The aim of this study (part of the RIVIERA project) is to analyse these groundwater-network interactions in a test sector, known for big quantities of parasite waters drained by the network and equipped with piezometers. In this sector of the Bordeaux agglomeration (France), a river is present and is draining the groundwater.

First, after a geological and hydrogeological characterization of the studied zone, a geostatistical analysis of piezometric data has been carried out in order to highlight annual and long-term water table cycles. The spatial analysis of data has also shown the influence of the distance to the river on the groundwater behaviour. Geostatistical tools have also been used to reconstruct incomplete piezometric time series. Then, with cross-correlations tools, the impact of effective rainfall (taking into account the true evapotranspiration) on water table fluctuations has been studied in order to quantify the phase difference between rain and groundwater recharging.

Secondly, various maps have been created with geostatistical tools: maps of low and high water table during a representative cycle, of lowest and highest water table at the pluriannual scale, of the maximal range of groundwater variations.

Finally, coupling these maps with sewer network depth allows establishing network vulnerability maps linked to the groundwater presence and its behaviour.

This study has allowed developing a methodology to study the impact of water table fluctuations on a sewer network.

Résumé: La prédiction de la durée de vie des réseaux d'assainissement est essentielle pour la gestion du patrimoine en milieu urbain. Lorsqu'une ou plusieurs nappes sont présentes dans le terrain contenant le réseau, les battements de celles-ci engendrent des variations de pression et des conditions d'altération physico-chimique néfastes pour le réseau et son environnement. Dans le cadre du projet RIVIERA (Risques en Villes : Equipement, Réseaux, Archéologie), une étude a été entreprise afin d'appréhender ces interactions nappe-réseau dans un secteur test connu pour l'importance des eaux parasites souterraines drainées par le réseau et suffisamment équipé en piézomètres, où circule un cours d'eau drainant une nappe libre, de l'agglomération bordelaise (France).

Premièrement, après une caractérisation géologique et hydrogéologique du secteur d'étude, une analyse géostatistique des données piézométriques a été menée afin de mettre en évidence des cycles de variations de hauteur d'eau annuel et pluriannuel. L'analyse spatiale des données a de plus montré l'influence de la distance au cours d'eau sur le comportement de la nappe. Les méthodes géostatistiques ont également permis de reconstruire les chroniques piézométriques incomplètes. Puis, à l'aide d'outils comme les corrélations croisées, l'impact des précipitations efficaces (prenant en compte l'évapotranspiration réelle) sur les variations du niveau de la nappe a été étudié afin de quantifier le déphasage existant entre pluie et recharge de la nappe.

Dans un second temps, différentes cartes ont été construites par méthodes géostatistiques : cartes des basses et hautes eaux de la nappe au cours d'un cycle représentatif, des plus basses et des plus hautes eaux à l'échelle pluriannuelle, d'amplitude maximale du battement de nappe.

Enfin, le couplage de ces cartes avec celle de la position altimétrique des réseaux d'assainissement a permis d'établir des cartes de vulnérabilité du réseau en relation avec la présence de la nappe et son comportement.

Le travail effectué a donc conduit au développement d'une méthodologie pour l'étude de l'impact des variations de la nappe phréatique sur les réseaux d'assainissement.

Keywords: Data analysis, Hydrogeological maps, Hydrology, Piezometers, Risk assessment, Shallow aquifers

INTRODUCTION

At an urban area scale, a lot of geological, hydrogeological or geotechnical information is available. The aim of the RIVIERA project (« Risques en Villes : Equipement, Réseaux, Archéologie ») is to use all these data in order to build tools for decision support. The first part of the project is to construct a consistent 3D geological model of the west side of Bordeaux agglomeration (France) (Dominique *et al.* 2005, Bourgine *et al.* 2006). Then three applications are derived from this macro-model in the archaeological, geotechnical (Breysse *et al.* 2006) and hydrogeological fields; this paper focuses on this last application.

Water table variations are of prime importance for a lot of applications in environmental and civil engineering (Finke *et al.* 2004) like for sewer networks behaviour for example. When a sewer network is implanted inside a saturated or partially saturated terrain, interactions between networks and groundwater are various: perturbation of underground flows by networks, hydraulic pressure on the network which can create damages. These network damages can cause the exfiltration of effluents in the groundwater (and so pollution of groundwater) or the infiltration of natural water or thin particles in the network; these parasite waters flowing in the network cause surplus of discharge and of cost of treatment. Damages can also cause terrain settlements or collapse and so road accidents. The aim of this work is to study the impact of water table fluctuations on sewer networks in order to establish risk maps which could be used to manage inspection campaigns on networks. A small area equipped with piezometers has been chosen in the north-west of Bordeaux to lead this study. This area has been chosen because the network drains a lot of parasite waters and because of the presence of numerous existing piezometers.

In a first part, we will present the studied area and piezometric data available on the site. Then we will apply geostatistical tools on these time series in order to analyse the spatial structure of this temporal data and to reconstruct incomplete time series. Finally, maps of piezometric surface will be built for high or low water table periods in order to study water table fluctuations. The final aim will be so to study the vulnerability of the network linked to these fluctuations.

PRESENTATION OF THE STUDIED AREA AND AVAILABLE DATA

The hydrogeological application of the Riviera project is carried out on a 36 km² area located at the north-west of Greater Bordeaux (**Figure 1**).

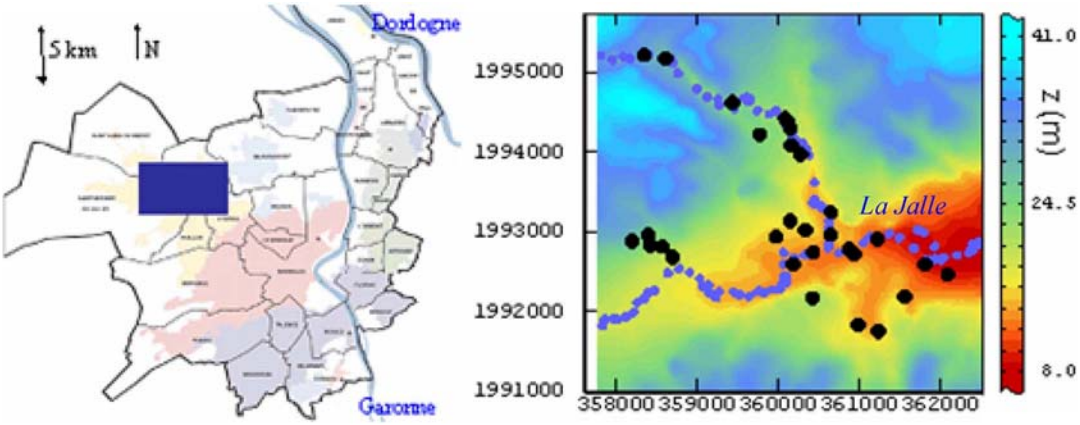

Figure 1. Greater Bordeaux and topographic map (Lambert 2 projection) of the studied zone. Black dots localize piezometers, blue dots are the rivers.

From a geological point of view, the geology of Bordeaux can be summarized as a staircase of terraces rested on a tertiary substratum with sub-parallels interfaces. More details on the geology can be found in Dubreuilh (1976) and Bourgine *et al.* (2006). Because the hydrogeological application concerns sewer networks, we will focus on shallow terrains. On the studied area shown on Figure 1, shallow geological formations are quaternary terrains (one of the terraces) principally composed of gravel, sand and more or less clayey formations. The tertiary substratum (limestone or calcareous clays) outcrops a little bit, in the La Jalle's valley for example.

From a hydrogeological point of view, groundwater is located inside the quaternary terrace which is an unconfined aquifer. This groundwater can communicate with other deeper aquifers like calcareous karstified aquifers for example. The main river on the site ("La Jalle") is also in communication with the groundwater. We want to characterize the variations of this piezometric surface in order to define the vulnerability of the sewer network.

In the studied area, 33 piezometers are installed and recorded time series are available since 15 years for the oldest (all piezometers have not been installed in the same time and some piezometers are not exploited today). Furthermore some piezometers have holes in their record for technical problems for example. Finally rainfall and evapotranspiration data are also available from Méteo France and will be used to study correlations between water table and rainfall. All these data will be analysed in the next part.

ANALYSIS OF PIEZOMETRIC DATA

Before analysing piezometric data, a pre-treatment is necessary to reveal possible anomalies. Two possible errors have systematically been verified:

- the accordance between the altitude of a piezometer and the topographical information available from the digital elevation model,
- the annual range of water table fluctuations in order to find abnormal measurements.

Possible errors have so been rectified or measurements deleted.

Temporal analysis

The temporal analysis of the 33 piezometers has several aims:

- characterize the evolution of the water table in time: are there piezometric cycles?
- reconstruct incomplete time series by geostatistical tools,
- analyze relations between rainfall and water table.

Piezometric cycles

The **Figure 2** shows two examples of a water table record over 13 years (two of the most complete time series).

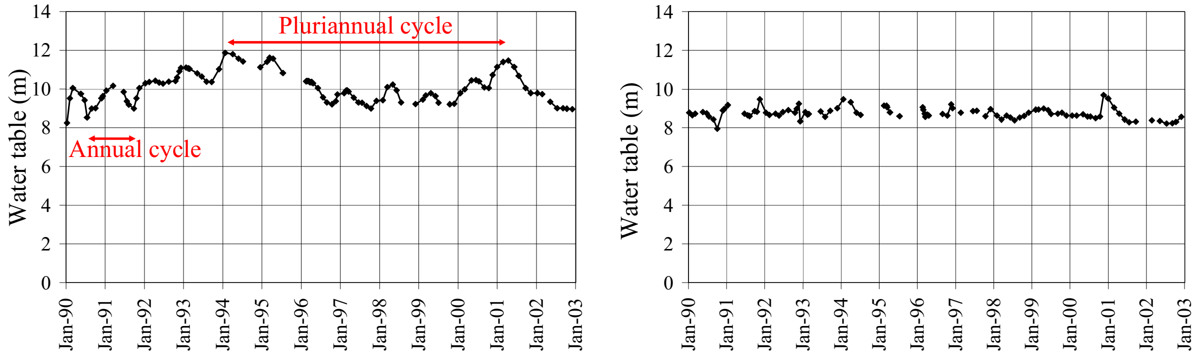

Figure 2. Example of two piezometric time series (left: far from “La Jalle”, right: close to “La Jalle”).

For a piezometer located far from “La Jalle” (main river on the sector), one can see on Figure 2 two main piezometric cycles: the first one is a classical annual cycle, with a maximum water table in February or March; the second one is a pluriannual cycle with a duration of about seven years between two high water table periods. Nevertheless, we have only thirteen years of measurement and it would have been interesting to have a longer recording period to confirm if the long-term cycle is repeated. The maximum range of water table is about four meters (between January 1990 and January 1994); if a sewer network is located at about ten meters height, it could suffer of damages due to water table fluctuations.

For a piezometer located closer to “La Jalle” (right graph on Figure 2), the annual cycle appears with smaller water table variations, but the long-term cycle doesn’t exist. Other parameters can influence the water table range or the presence or not of a long-term cycle as for example the urbanization rate.

Furthermore, the time series show a period without measurement, for example between the end of 1995 and the beginning of 1996. On this example, this period is short but other piezometers have longer lacks of measurement. If we want to map the water table at a given date, it is necessary to have a maximum of water table values at this date. That is why a geostatistical work has been done in order to reconstruct incomplete time series.

Reconstruction of incomplete time series by geostatistics

Geostatistics is a powerful tool in order to characterise the spatial or temporal structure of data. Furthermore, it allows interpolating data by taking into account their spatial or temporal correlation. The basic geostatistical tool is the variogram which can be computed experimentally as follows (Chilès & Delfiner 1999):

$$\hat{\gamma}(h)=\frac{1}{2N_h}\sum_{x_j-x_i\approx h}\left[z(x_j)-z(x_i)\right]^2$$

where z is the value of the studied variable, x_i and x_j are the locations of points (in space or time), h is the lag vector, and N_h is the number of pairs of points, the distance apart of which is approximately equal to time lag h.

If we apply this equation to piezometric time series, z is the water table and h the time lag between two measurements. **Figure 3** shows a piezometric time series and the resulting variogram. In practice, the variogram is computed for lags h up to half the maximum interval between records (here six years).

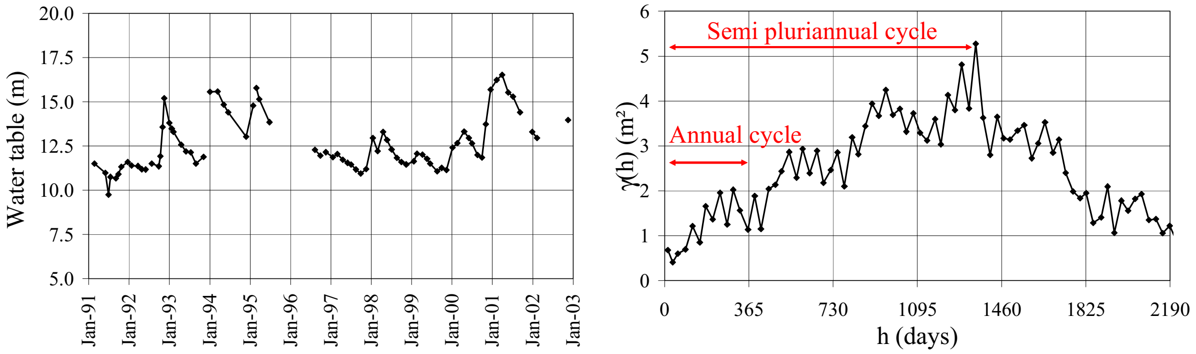

Figure 3. Piezometric time series and corresponding variogram.

The piezometric time series shows a water table record over twelve years but with holes for some periods (between august 1995 and september 1996 for example). Annual cycles are visible but the pluriannual cycle doesn't appear clearly.

The variographical tool allows identifying temporal structure of the water table. The variogram shows the evolution of $\gamma(h)$ as a function of the lag time h. On such a graph, a cycle is identified if the variogram value is the same for a lag value and for a greater lag value, the cycle period being the difference between both lags. In a same way the semi-period corresponds to the maximum difference in variogram values. On the variogram shown Figure 3, one can see a global increase of the chart up to a lag equal to three and half years, then a decrease of the function: we find by the variographical tool the value of the long-term piezometric cycle, equal to seven years which is the same value as the one identified on Figure 2. Inside this global cycle, we can see smaller structure for each yearly lag: in the rising phase of the variogram, we see stabilization of the variogram for 365 days, then for 730 days (two years)... These smaller structures emphasize the annual piezometric cycle. Finally, one can see a nugget effect on the variogram which corresponds to a discontinuity at the origin being the expression of quick variations of the water table in a short time.

After the identification of temporal correlations, we want now to reconstruct the piezometric time series in order to obtain an estimation of the water table for periods without measurements. This work must be done in two steps: modelling the experimental variogram by an admissible model, then interpolating lacks of measurements by kriging (using the Isatis® software (Geovariances 2005)).

The variogram model must be fitted to the experimental one and it is very important that the model takes into account piezometric cycles identified previously. Variogram models with periodicity are called hole effect models in geostatistics, such as the sinus-cardinal model which has been used here (adding to a nugget effect). Furthermore, in the kriging procedure used for interpolation, we will use experimental points maximum 900 days distant from the point to estimate; so the variogram model has to be fitted with care up to 900 days. Then by using this variogram model and this moving neighbourhood equal to 900 days, a kriging procedure is applied to reconstruct the time series, i.e. to obtain a water table value for each month. Figure 4 shows results of the variogram fitting and of the reconstruction.

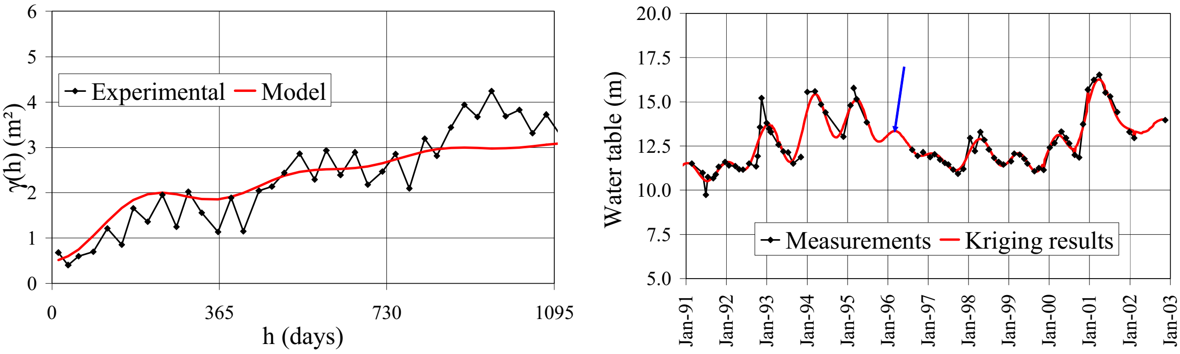

Figure 4. Variogram fitting (focus on a maximum distance of 900 days) and reconstruction of the piezometric time series by kriging.

The red chart on the reconstructed time series shows the result of the kriging procedure. One can see that we reproduce the original time series with a slight smoothing effect which is normal with this technique; in fact, kriging is the best interpolator in terms of reconstruction error, but has smoothing consequence in return (see at the end of 1992 for example). What is very interesting is the water table estimation during the period without measurements (between August 1995 and September 1996). During this period, the kriging reconstruction (based on a hole effect variogram model) allows estimating an annual piezometric cycle which had not been measured experimentally (see the blue arrow on the graph). We can see with this example the great advantage of geostatistical methods compared to others interpolation methods: the missing cycle wouldn't have been estimated with a simpler interpolation method.

For other piezometers, records are not numerous enough to apply this approach. Another way to estimate water table is to use an auxiliary variable such as rainfall for example.

Cross-correlations between water table and rainfall

When it is raining, a part of the water infiltrates in the soil and flows to the groundwater; so we can record a delay between rainfall and water table variations. Tools such as cross-correlations allow quantifying this delay. Because a part of the rain runs off, evaporates or is used by plants, water being able to flow to the groundwater is called effective rain. This effective rain can be computed as follows:

$$R_{eff} = R - R_{ETR} - R_{run-off} - R_{UR}$$

where R_{eff} is the effective rain, R the total rainfall, R_{ETR} the true evapotranspiration component, R_{UR} the run-off part and R_{UR} the part contributing for the refill of usable reserves for plants.

To study correlations between two variables, the cross-correlogram can be used:

$$R(h) = \frac{1}{N_h} \sum_{x_i - x_j \approx h} \frac{\left(z(x_i) - \bar{z}\right)\left(y(x_j) - \bar{y}\right)}{\sigma_z \sigma_y}$$

where z and y are the values of the both variables ($\bar{z}$ and $\bar{y}$ are the variable means and σ_z and σ_y their standard deviations), x_i and x_j are the locations of points, h is the lag vector, and N_h is the number of pairs of points, the distance apart of which is approximately equal to lag h. R is a correlation coefficient and is bounded by -1 and +1.

Figure 5 shows a piezometric time series (the same as on Figure 2) and the associated effective rainfall, and the resulting cross-correlogram.

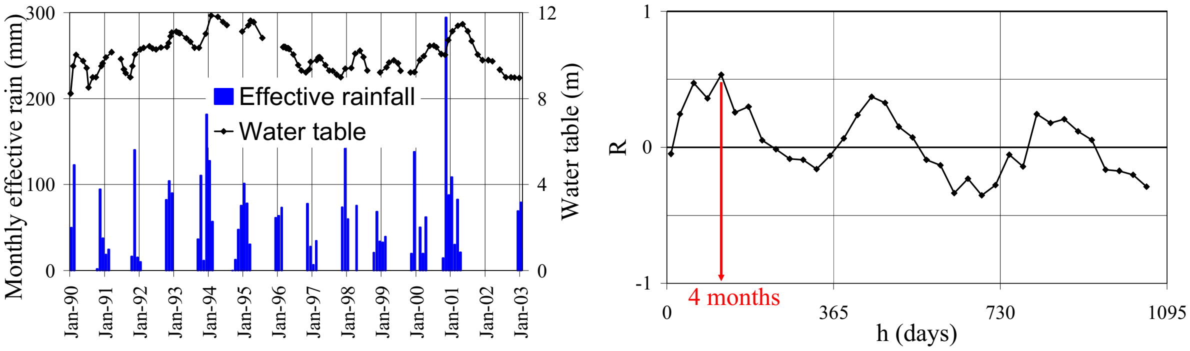

Figure 5. Piezometric time series with the associated monthly rainfall and cross-correlogram between both variables.

One can see that during a year, the effective rainfall is classically maximal during the autumn and null during the spring and summer. Furthermore, water table variations seem to be linked to effective rainfall and the cross-correlogram allows quantifying that. On this graph, the maximum of correlation between water table and rain is observed for a time delay equal to four months (R = 0.55). However this correlation coefficient value isn't very great, but this work allows estimating in average the delay between rainfall and water table variations. This delay is also dependent of the piezometer position: close to "La Jalle", the delay is shorter due to a shallower water table.

Thanks to the geostatistical work, we have now for each month of the recorded period a water table value either measured or estimated by kriging. It is so possible to compute a map of the water table whatever date we choose.

MAPS OF PIEZOMETRIC SURFACE

Mapping the piezometric surface consists in interpolating information available from time series. Because of the long-term aim of the study (risk concerning sewer networks), various piezometric surface maps can be realized: map at a given date or map of highest water table over the recording period for example.

In order to calculate these maps, various interpolation methods are available, the most accurate being the geostatistical tool. However, in this case, an accurate geostatistical work (with variogram modelling) hasn't been done because computed experimental variograms weren't statistically representative. If we look at the spatial localization of piezometers (Figure 1), most of them are aligned in a NW-SE direction. So variograms can be computed in this direction, but in the other directions the variographical information is of poor quality. Because anisotropy in water table spatial structuring could exist and this information isn't available in our case, we have chosen to not fit experimental variograms here to avoid great errors in interpolation. All interpolations have been done with the linear model kriging method allowing to attach more representative weights to experimental points than with other methods (like inverse square distance for example). In this method, the used variogram model is: $\gamma(h) = |h|$. Furthermore, after each interpolation, it is needed to check if the piezometric surface is completely below the topography, if not, some corrections are necessary.

Maps of low and high water table for a given date

A first kind of map that we can calculate is the piezometric surface at a given date. We present here two contrasted dates: one for a high water table period (January 1993) and the other for a low water table period (September 1991) (Figure 6, Lambert 2 projection). On this figure, white areas correspond to non-interpolated sectors because they are too far away from piezometers.

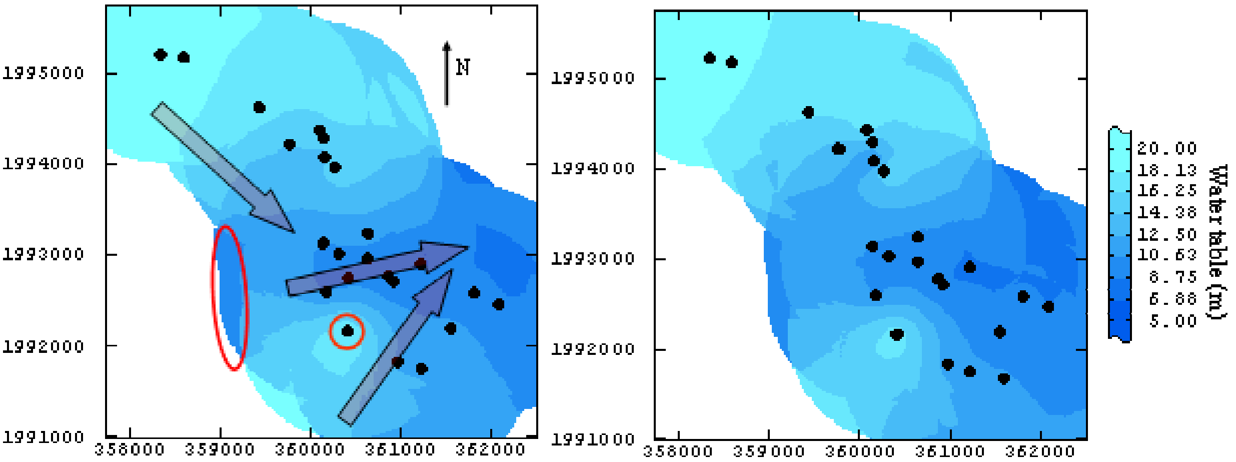

Figure 6. Piezometric surface for a high water table period (on the left) and a low water table period (on the right). Dots represent the piezometers used for the interpolation and arrows the flow direction; red areas are unusual zones as explained below.

One can see that flow directions are the same during a high or a low water table period: in the north part of the sector flow direction is globally NW-SE, in the south part SW-NE and W-E in the middle of the map. These flow directions are in accordance with the topography and with rivers flow direction (there is flow convergence toward "La Jalle").

On both maps, two unusual zones appear surrounded in red on Figure 6. The first one, located on the west side, is unusual because it is in disagreement with the flow direction; the big distance from this zone to piezometers has consequences on the interpolation quality. The second one is the zone around the surrounded piezometers; one can see here a piezometric dome which seems unusual in such a terrain. An explanation to this dome could be a local variation of the lithology resulting in a disconnected perched groundwater; if this hypothesis is verified in future, this piezometer will be deleted for the interpolation.

Maps of lowest and highest water table at the pluriannual scale

Because we need to know the maximal water table fluctuation, we can map the highest and the lowest piezometric surface during the recording period (13 years). For this, we pick up the maximum (or minimum value) of the water table over the record period for each piezometers and we interpolate in the same way as before (Figure 7). It is to notice that non-interpolated zones are smaller than before because more piezometers are available on the whole recording period.

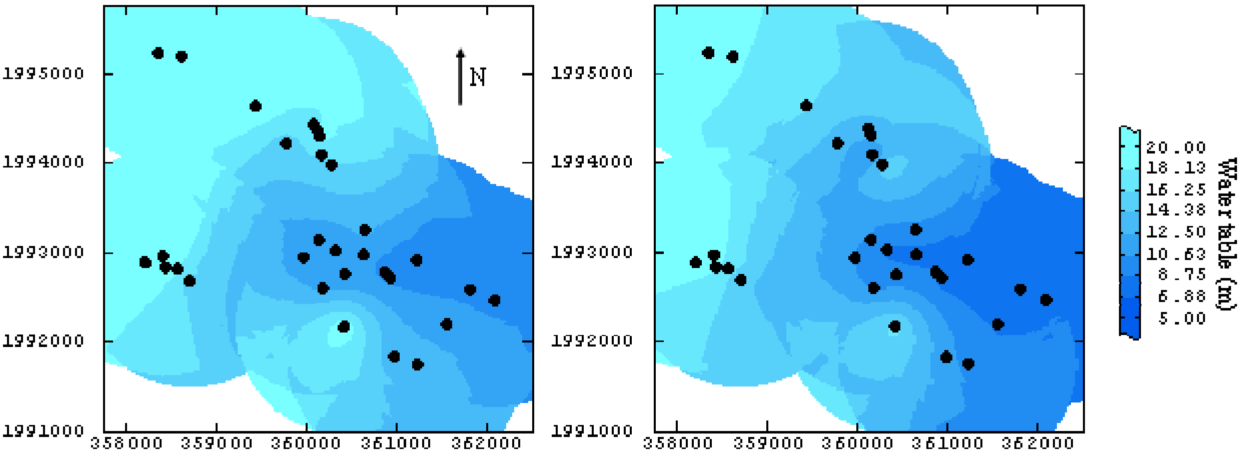

Figure 7. Maps of the highest (on the left) and the lowest (on the right) water table (Lambert 2 projection).

We have with these maps superior and inferior envelopes of the piezometric surface. From all these kinds of maps we can now easily deduce water table variations.

Maps of water table variations

A map of water table variation is computed by the difference between the maps of high and low water table. This work can be done between two given dates (maps of Figure 6) or to find the maximal water table variation during the whole recording period (from both maps shown Figure 7) (Figure 8).

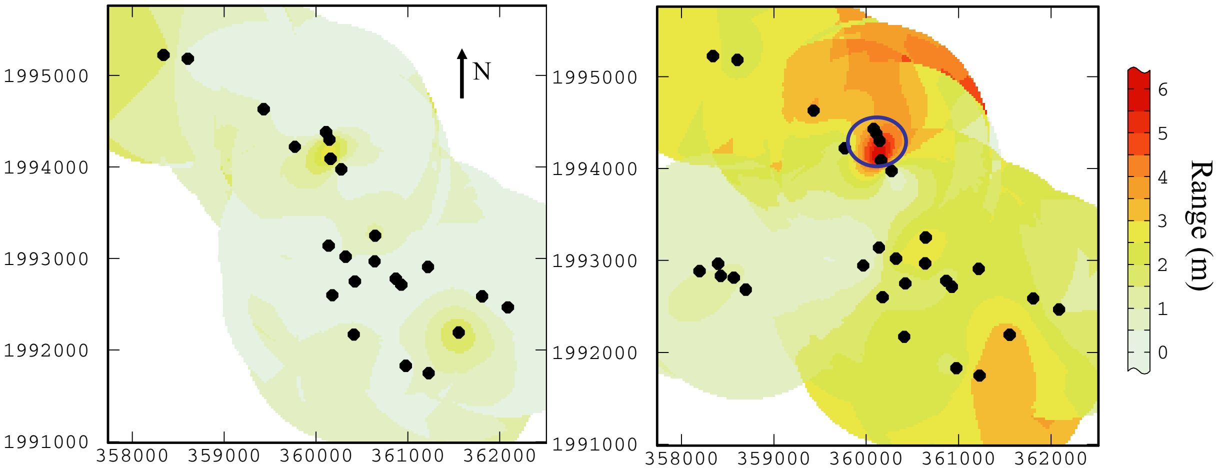

Figure 8. Range between high and low water table (Lambert 2 projection): on the left between two close dates, on the right the maximal range over 13 years. The blue area shows the maximal range zone.

When we study the water table range between two close dates (September 1991 and January 1993), one can globally see small ranges: the maximum range is equal to 3 m and the mean range to 0.5 m. If we look now at the map showing maximum ranges (Figure 8 on the right), observed values are obviously greater: the mean is now equal to 2.1 m with a maximum equal to 6.6 m (surrounded zone in blue on the map). If we compare both maps, areas with small or high water table variations are located in the same place and main differences are quantitative.

The main differences between sectors on the map are closely linked to conclusions of Figure 2: the closer “La Jalle”, the smaller the range is or the more elevated a piezometer, the greater the range is. Furthermore piezometers in the surrounded zone in blue (maximum range) are located in wooded area contrary to piezometers located on the west side of the studied zone, what confirms influence of urbanization rate on groundwater behaviour.

From all these maps, it is now possible to study the interference between groundwater and sewer networks.

VULNERABILITY OF SEWER NETWORK LINKED TO WATER TABLE FLUCTUATIONS

The aim is now to analyse the vulnerability of a sewer network as a function of water table fluctuations. Various cases can be found (**Figure 9**).

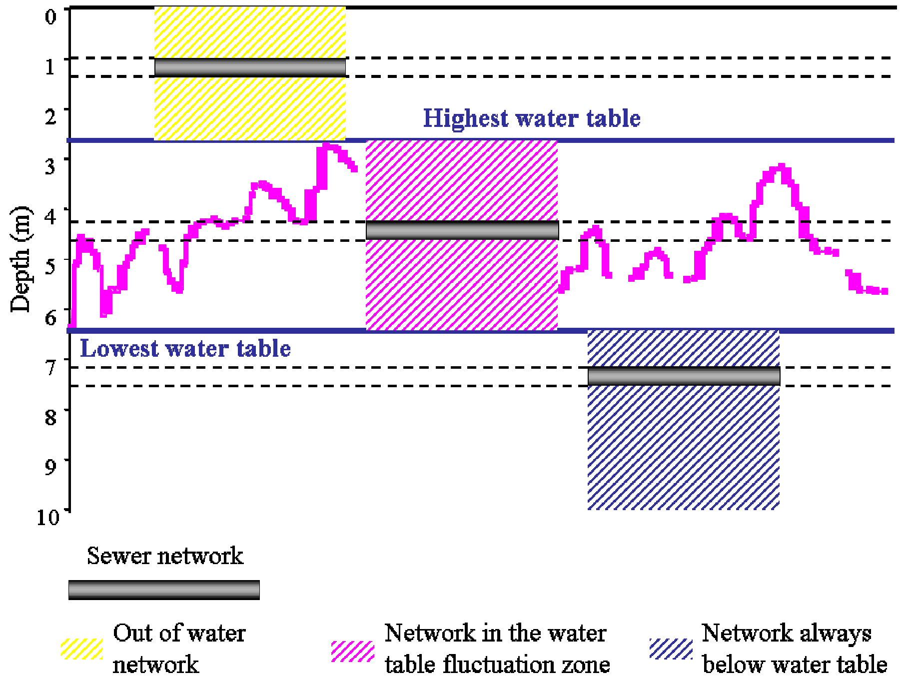

Figure 9. Possible locations of a sewer network as a function of the water table.

One can see on Figure 9 that three cases can exist: a sewer network can be located either always above the water table (case 1) or always below the water table (case 2) or in the water table fluctuation zone (case 3). This last case (case 3) is the most harmful for sewer networks weathering, following by the case 2 and by the case 1 (however in this last case others damage causes can exist but we focus here only on damages due to water table fluctuations). The case 3 is the most damaging because the network is alternatively above or below the water table what induces great mechanical conditions variations and possible phases of infiltration or exfiltration if the network is weathered. Furthermore, damages on surrounding areas can appear, road collapse for example. Knowing the elevation of the sewer network and combining it with maps previously shown, it is now possible to classify the network with the three cases of Figure 9 (Figure 10).

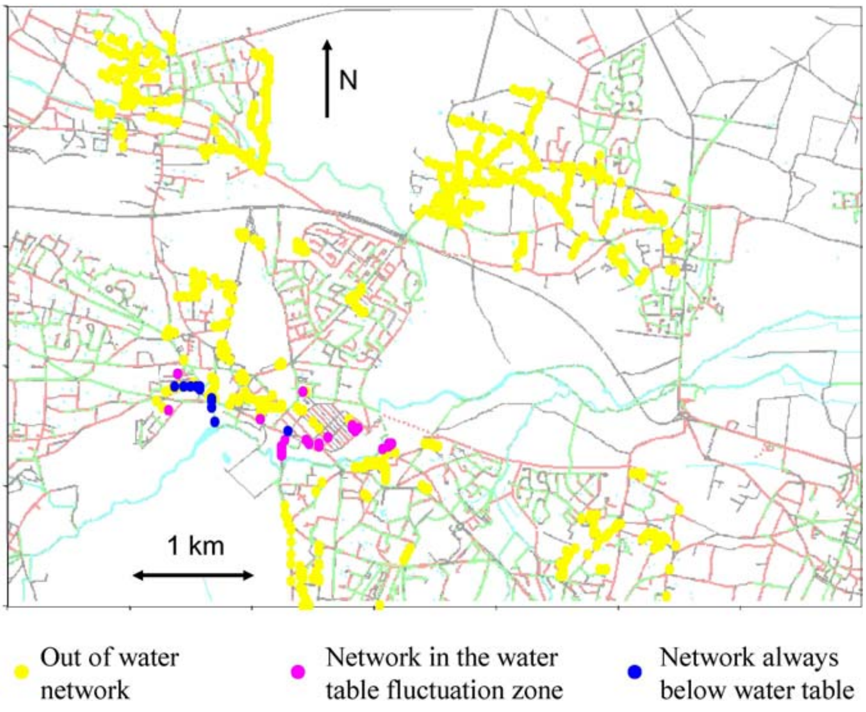

Figure 10. Map of the vulnerability of a part of the sewer network as a function of water table fluctuations.

This map provides a first tool to manage future inspection campaigns. However, this approach has to be improved in order to distinguish several cases when the network is located in the water table fluctuation zone. Indeed the time ratio “network below water table / network above water table” has to be taken into account. Furthermore, for a same ratio equal to 1 for example, it is not the same condition if the network is during a year six months above water table and six months below water table or if it is six times one month above water table and one month below water table.

CONCLUSIONS AND PERSPECTIVES

In an urban environment, geotechnical or hydrogeological risks are numerous; the RIVIERA project aims to develop management decision tools to orientate inspections or works. Concerning sewer networks, a great part of possible damages are related to water table fluctuations inducing mechanical damages on networks and infiltration or exfiltration between network and groundwater.

Starting from 33 piezometers located on a 36 km² sector of the Greater Bordeaux, the first part of the study had been to analyse piezometric time series in order to identify cycles (annual and pluriannual). Incomplete time series have been reconstructed by geostatistical tools allowing estimating water table values for non recorded periods. Geostatistical tools are powerful in such a case allowing finding non recorded piezometric cycles and identifying delay between rainfall and groundwater variation. From these time series, piezometric surface maps have been computed for various conditions of high or low water table periods. Coupling these maps to elevation of sewer networks allows estimating a vulnerability index of the network as a function of water table conditions.

Several perspectives are to develop. First, the map of the vulnerability of the sewer network as a function of water table fluctuations has to be improved by taking into account various conditions when the network is located inside the water table fluctuation zone. Secondly, up to now we have considered a unique unconfined aquifer in the zone. However, this aquifer shows lithological heterogeneities such as more clayey parts for example. These variations in the lithology can induce variations in groundwater flow with disconnected perched aquifers for example. That is why a 3D lithological model is developed to take this parameter into account in risk maps. Finally, after the risk maps improvement, results will be compared with video network inspections to validate the model. This described methodology aims to provide useful management tools for urban decision makers.

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