Technical note: Water table mapping accounting for river-aquifer connectivity and human pressure

Maillot Mathias[1-2], Nicolas Flipo[1], Agnès Rivière[1], Nicolas Desassis[1], Didier Renard[1], Patrick Goblet[1], and Marc Vincent[2]

[1]Geosciences Department, MINES ParisTech, PSL University, Fontainebleau, France
[2]EPTB Seine Grands Lacs, Paris, France

Correspondence: Maillot Mathias (mathias.maillot@mines-paristech.fr), Nicolas Flipo (nicolas.flipo@mines-paristech.fr)

Abstract. A water table mapping method that accounts for surface water-groundwater (SW-GW) connectivity and human pressure, such as pumping and underground structures occurrence, has been elaborated and tested in the heavily urbanized Parisian area. The method developed here consists in two steps. First, hard data (hydraulic head) and soft data (dry wells) are used as conditioning points for the estimation of the SW-GW connection status. A disconnection criteria of 0.75 m is adjusted on observed unsaturated zone depth (UZD). It is a default value in areas where such data are missing. The second step consists in the final mapping of water table. Given the knowledge of the disconnection criteria, the final map is achieved with an ordinary kriging of the UZD that integrates the surface water elevation as a nil unsaturated zone where it is relevant. The methodology is demonstrated on two datasets of UZD observations that were collected under low and high flow conditions.

1 Introduction

Water table maps are key tools for water resources and flood risk management. A way to characterize a water table distribution is to describe it using piezometric maps. Albeit this seems an obvious statement, some methodological aspects require further development, such as the way how to take into account uncertainty about surface water (SW) and groundwater (GW) connectivity.

This connectivity status can be either connected~~or disconnected~~, transitional or disconnected (Dillon and Liggett, 1983; Fox and Durnfor For the connected case, the surface water elevation corresponds to the water table ~~below the riverbed~~ and should be accounted as an observation sample ~~(Chung and Rogers, 2012)~~(Chung and Rogers, 2012; Winter et al., 1998), whereas surface water level should not be considered into mapping in the disconnected case (Hentati et al., 2016).

The river-aquifer connectivity status depends on hydrological and geological parameters such as the surface water level, water table, riverbed geometry and hydrogeological parameters of the substratum (Brunner et al., 2009; Peterson and Wilson, 1988; Rivière et al., 2014). Water table and surface water level distribution results from precipitation, recharge of aquifers, topography, riverbed and aquifer geometries, and hydrodynamic parameters ~~(Flipo et al., 2014)~~(Flipo et al., 2014; Bresciani et al., 2016). Urban GW are seriously affected by the development of urban areas. Indeed, human settlement nearby fluvial environments results in significant SW and GW decline due to pumping wells for domestic and industrial usages, as well as for underground

Summary of Comments on hess-2019-101-AC4-supplement_4_ed.pdf

Page: 1

Number: 1 Author: Subject: Highlight Date: 9/17/19, 11:31:14 AM

structure protection and the construction of underground infrastructures (Morris et al., 2003; Attard et al., 2016; Machiwal et al., 2018; Schirmer et al., 2013). Moreover, the development of ~~embankments~~ levees along the river and riverbed dredging generate major modifications of the stream-aquifer status. So far, all those aspects have not been taken into account in water table mapping methodologies.

The most commonly used methods for the estimation of a continuous variable are ~~usual~~ linear estimators, neural network and kriging (Varouchakis and Hristopulos, 2013). The main linear estimators are inverse distance weighting (Gambolati and Volpi 1979, Philip and Watson 1986, Rouhani 1986, Buchanan and Triantafilis 2009, Sun et al. 2009) and influence polygon or moving average (Vicente-Serrano et al., 2003). ~~Varouchakis and Hristopulos (2013) compared these different methodologies and showed that kriging provides better performance~~ These different methodologies were compared in several studies and kriging was found out as a better estimator in terms of cross-validation ~~than~~ and performance than the other linear interpolators (Varouchakis and Hristopulos, 2013; Emadi and Baghernejad, 2014; Adhikary and Dash, 2017; Ohmer et al., 2017) . Although the linear estimation methods provide unbiased results, they do not account for the spatial heterogeneity of the samples distribution. The estimated value depends either on the nearest sampled value (influence polygon), or on every sampled values surrounding the estimation point (moving average) regardless the distance between the estimation point and each individual sampling point. Inverse distance weighting involves the arbitrary choice of the distance degree. The distance degree is a conditioning setting for the variability of estimated fields whereas kriging involves a weighting of observation that is consistent with the spatial distribution of the variable.

Recently, interpolations based on fuzzy logic or neural network derived methods have been tested (Kurtulus and Flipo, 2012; Sun et al., 2009). These methods are still suffering of a main drawback, that is they produce results without coherent spatial error structures (Flipo and Kurtulus, 2011). The diffusion kernel interpolation method used in Bresciani et al. (2018) showed good results for large datasets. This method is based on geographically weighted regression which aims to map the trend of a variable (Gribov and Krivoruchko, 2011) . Depending of the used parameter in the application of this methodology, the produced map can be very smoothed or noisy. This method allows for the spatial representation of estimation error, nevertheless there is no guaranty that the resulting map honors the input data.

A widely accepted solution that provides information on estimation errors is kriging (Chilès and Delfiner, 1999; Matheron, 1955). It can be applied on different types of variables (Cressie, 1990) including water table (Hoeksema et al., 1989). Many studies produced water table maps resulting from kriging in order to describe water table distributions (Ahmadi and Sedghamiz, 2007; Bhat et al., 2014; Buchanan and Triantafilis, 2009; Chung and Rogers, 2012; Hentati et al., 2016; Hoeksema et al., 1989; Kurtulus and Flipo, 2012; Mouhri et al., 2013; Zhang et al., 2018). Rouhani and Myers (1990) noticed that water table data displays spatial nonstationarities, which are due to the ~~topographic slope~~. Such nonstationarities cause problems in the determination of the experimental variogram and also generate large standard deviations of the estimation errors. A way to overcome the issues linked to nonstationarities was proposed by Desbarats et al. (2002). Their methodology also based on kriging was developed for an unconfined aquifer. It relies on the spatial correlation between the water table and the topographic surface (King, 1899; Toth, 1962). This assumption was established by Desbarats et al. (2002) at large scales considering several watersheds. Haitjema and Mitchell-Bruker (2005) proposed that: "shallow aquifers in flat or gently rolling terrain may exhibit

Page: 2

Number: 1 Author: Subject: Highlight Date: 9/17/19, 11:34:27 AM

As suggested by reviewer 2, please also mention the potential for leaky sewer and water supply plumbing networks to recharge groundwater and act as drains (in the case of sewers) that limit how shallow the water table can rise in some areas.

Number: 2 Author: Subject: Inserted Text Date: 9/17/19, 11:37:44 AM

gaurantee

Number: 3 Author: Subject: Inserted Text Date: 9/17/19, 11:39:32 AM

directional trends in hydraulic head gradients a relatively low of recharge over hydraulic conductivity ratio and still exhibit a water table that seems a subdued replica of the terrain surface"(Haitjema and Mitchell-Bruker, 2005, p786). This methodology, that targets the unsaturated zone depth (UZD) instead of the hydraulic head, leads to lower values of the standard deviation of the estimation error for unconfined aquifer in non-urbanized area (Kurtulus and Flipo, 2012; Mouhri et al., 2013; Rivest et al., 2008; Sağir and Kurtuluş, 2017).

In urbanized area, the pumping of GW implies the decline of water table, which could lead to the ~~dry~~ drying out of a few piezometers. The knowledge of a dry well can be added to a dataset in the form of an inequality (i.e. UZD larger than the well depth) (Michalak, 2008). The counter part of accounting for such information translated into a mathematical inequality is that it is incompatible with kriging itself. Therefore another methodology has to be used for water table mapping in such environments.

A solution is the usage of multiple conditional simulations that provides a conditional expectancy map of the variable. Its application in hydrogeology was demonstrated for hydrofacies determination (Dagan, 1982), converting lithofacies into hydrofacies to constrain groundwater flow models. This study proved that the use of conditional probability reduces the variance of possible values of the targeted variable, for instance here hydrofacies properties. This methodology was applied in different geological contexts (Tsai and Li, 2007; Dafflon et al., 2008) proving its robustness and has not been applied to the UZD so far.

~~Another source of uncertainty in water table mapping methodology is the fact that over a large area, such as a watershed or basin, the water table distribution is also driven by the recharge rate of the aquifer (Haitjema and Mitchell-Bruker, 2005). To avoid this drawback, our methodology assumes a nil recharge, which is the case in urbanized areas where a high degree of soil sealing is observed.~~

The mapping methodology presented in this paper relies on the assumption that the UZD variable is related to the topographic elevation and the river water level. ~~One~~ The second assumption is that UZD is not related to the stream water level in the case of a disconnected hyporheic zone. Therefore, it can be applied to superficial aquifer units submitted to human pressures and other locations where the SW-GW connectivity is uncertain. The following questions are addressed: (i) which ~~method is the most relevant~~ methodological steps are required for water table mapping in alluvial plains? (ii) how to account for human practices such as pumping in the mapping methodology ? (iii) how to ~~define~~ determine the SW-GW connection status? (iv) finally, what are the consequences of such methodological refinements on produced maps of water table linked to hydrological events?

2 Mapping Methodology

Water table mapping was initially developed for the description of regional aquifers into natural or pristine environments. The usual way of mapping a water table is to use synchronous UZD measurements resulting from snapshot campaigns. The synchronization of measurements is crucial to avoid experimental bias (Tóth, 2002). This section describes a methodology that combines conditional simulations of UZD, with an assessment of SW-GW connectivity and a final ordinary kriging of the UZD. Geostatistical processings are performed using the RGeostats R package (Renard et al., 2001 - 2019).

Fig. 1. describes the methodology. Firstly, the ~~dataset analysis is achieved in order to constitute the raw dataset for mapping~~raw dataset is composed of each measured UZD for the corresponding measurement campaign. The raw dataset is then transformed

Number: 1 Author: Subject: Highlight Date: 9/17/19, 11:40:25 AM

word missing

into a Gaussian score dataset using an anamorphosis function fitting in order to obtain a Gaussian probability density function (Chilès and Delfiner, 1999). Inequality constrained samples (dry wells) are estimated using a Gibbs sampling of the Gaussian score ~~dataset~~ subset (Geman and Geman, 1984; Freulon and de Fouquet, 1993). Thereafter, one hundred turning band simulations (Matheron, 1973) are performed and averaged before their backtransformation into the real data. A first guess map of water table is obtained averaging all back transformed simulations. The SW-GW connectivity status is deduced from the first guess map following a new connectivity criteria that permits to constitute the final UZD dataset. The final water table map is finally produced performing an ordinary kriging of the final UZD dataset that is removed from a reference Digital Elevation Model (DEM) of the ground.

2.1 First Guess - Simulations without considering the river water level

The initial dataset is made of hard data and soft data. The hard data are UZD measured during snapshot campaigns. The soft data are dry well depths. The dataset is characterized in terms of spatial statistics in order to justify the use of an appropriate geostatistical tool. UZD is defined in terms of a non-Gaussian probability density function conditioned with non-negativity constraint. Unlike water table, UZD can be considered as a continuous stationary variable. The supposed stationarity of a variable makes it usable for ordinary kriging methodologies. In other cases, more complex non-stationary geostatistics should be applied, requiring hypothesis about the estimated variable.

2.1.1 Input data pre-processing & DEM smoothing

The use of UZD as a variable ~~to map~~ for mapping the water table requires to refer to the elevation of the ground from which water table can be ~~deduced~~ ~~from~~. In our approach the elevation of the ground is approximated using a smoothed DEM, called reference DEM. It is obtained merging a DEM and river water levels. This merged DEM is smoothed (Fig. 1., step 1) using SAGA GIS algorithm (Conrad et al., 2015) for moving average filtering~~(the search radius is~~ , this methodology was already proposed by Mouhri et al. (2013). The smoothing of the DEM is required to avoid the occurrence of high frequency topography signals that would not be relevant with the ~~average width value of the stream network) .~~ water table signal. The search radius is defined regarding two conditions: i) the DEM has to be smoothed enough to remove its high-resolution noise and ii) the information of river water level must be conserved in the final product. We tested several ~~radius~~ to fit these conditions and found out an appropriate value of 325 m.

The difference between ~~the actual wellhead elevation and the smoothed DEM data at sampling points can be important at locations where topographic gradient is locally high, especially into~~ rough DEM and smoothed DEM may be important in locations where the topographic slope is the most important. These locations include crucial areas nearby the riverbanks. Therefore, this difference is calculated at each sampling point. Due to the use of UZD, this ~~may generate~~ generates a biased estimation of water table at these locations, given that this difference is not yet accounted for into the UZD measured value. The way to tackle the DEM smoothing effect is to constitute a first data subset, deducting the difference between smoothed DEM data and true wellhead elevation from the raw UZD data before ~~to~~ proceed with the next steps of our procedure (Fig. 1). For the sake of readability, this first data subset will still be called UZD raw dataset in the remaining of the paper.

Number: 1 Author: Subject: Highlight Date: 9/17/19, 11:47:57 AM

Not clear. Do you mean "subtracted from"? Is this the step where you convert the UZD map into a head map?

Number: 2 Author: Subject: Highlight Date: 9/17/19, 11:59:14 AM

This is not true as a blanket statement. It may be true in cases where the water table and topography, including their gradients, are variable spatially. But inherently the water table, topography and UZD are directional. This leads to a type of non-stationarity in which the expected value and it's variance differ dramatically when looking perpendicular to the gradient versus looking parallel to the gradient. In the former, at the local scale, there is no change in the variable, and the variance is nil. In the latter, at the local scale, the spatial variance increases parabolically and never reaches a sill if the gradient is uniform. So, perhaps the quick way out of this conundrum is for you to assert that the directional gradients in UZD are much less pronounced or more irregular than the h gradients, making it more amenable to treatment with stationary geostatistics. In the sentence that follows, you should make it clear that if there are significant trends in the data, then geostatistica approaches that account for that can be applied, such as universal kriging (cite a geostats text such as Goovaerts).

Number: 3 Author: Subject: Inserted Text Date: 9/17/19, 12:00:11 PM

computed

Number: 4 Author: Subject: Inserted Text Date: 9/17/19, 12:01:13 PM

radii

Number: 5 Author: Subject: Cross-Out Date: 9/17/19, 12:01:42 PM

Number: 6 Author: Subject: Cross-Out Date: 9/17/19, 12:02:06 PM

Number: 7 Author: Subject: Inserted Text Date: 9/17/19, 12:02:13 PM

ing

2.1.2 Hard data selection & variograms

The variographic analysis of the UZD raw dataset is achieved in order to describe the variability of UZD ~~into~~ in a 2D domain. In urbanized area, anthropic pressure such as permanent pumping, affects the natural correlation between DEM and UZD with the occurrence of local piezometric depletions. In terms of experimental variogram, the use of samples affected by anthropic pressure induces a drastic increase of the semi-variogram value. This cannot be considered as a representative variability of the ~~global~~ UZD variable. To prevent this effect on the experimental variogram calculation, the original dataset is divided into two categories (Fig. 1., step 2). The first category regroups all samples where the UZD value is affected by the pumping wells. The ~~samples with UZD value greater than~~ second category is composed by the other samples. Information about the locations of pumping wells is required to identify these samples. In this study, the locations and pumping flow-rates are not available. The affected and unaffected piezometers are differentiated regarding the correlation between topography and water table. Grubb (1993) stated that water table within the capture zone of a pumping well is not hydrostatic, then it is assumed that topography and water table are not correlated within this capture zone. The samples where there is no correlation between topography and water table are identified as the affected samples.In this study, samples with a UZD value exceeding 10 m ~~are grouped in this category. The second category is composed by the other samples. All~~ were found in that category. Note that this value may vary according to the case study. This differentiation is required to elaborate a geostatistical tool (i.e. variogram model) that only depends of natural variability. Therefore, all the variographic studies are performed on this second category called unaffected UZD dataset. 1

The experimental variograms are calculated on two types of ~~variable~~variables: the Gaussian score used in the Gibbs sampling and conditional simulations, and the unaffected UZD dataset for the final ordinary kriging procedure. The Gaussian score variable used for Gibbs sampling-conditionnal simulation steps is described in the next subsections. UZD is the variable ultimately used for ordinary kriging. Each calculated experimental variogram is a representation of the spatial variability of the dataset. A variogram model is fitted to each experimental variogram with a composition of spherical, exponential and cubic functions. The variogram fitting is achieved using an automated procedure (Desassis and Renard, 2013).

2.1.3 Anamorphosis function fitting

In order to handle the non-Gaussian behavior of the UZD, one possibility is to transform a random function into a Gaussian function using an anamorphosis function fitting such that $\varphi = F^{-1} \circ G$, where φ is the anamorphosis function, F the continuous marginal distribution function of unaffected UZD, and G the cumulative density function of the Gaussian score (Chilès and Delfiner 1999). First, the cumulative histogram of the unaffected UZD dataset is established. Therefore, the corresponding Gaussian score is empirically obtained using the frequency inversion of unaffected UZD. The unaffected UZD dataset is transformed into a Gaussian score dataset using an anamorphosis function (Fig1. step 3). This transformation was already used by Flipo et al. (2007) to study aquifer contamination by nitrates.

Number: 1 Author: Subject: Inserted Text Date: 9/17/19, 12:19:57 PM

While the above procedure was used to roughly approximate which wells are affected by pumping, any future applications of the method outlined in this technical note should identify the wells impacted by pumping using actual data on pumping rates and locations.

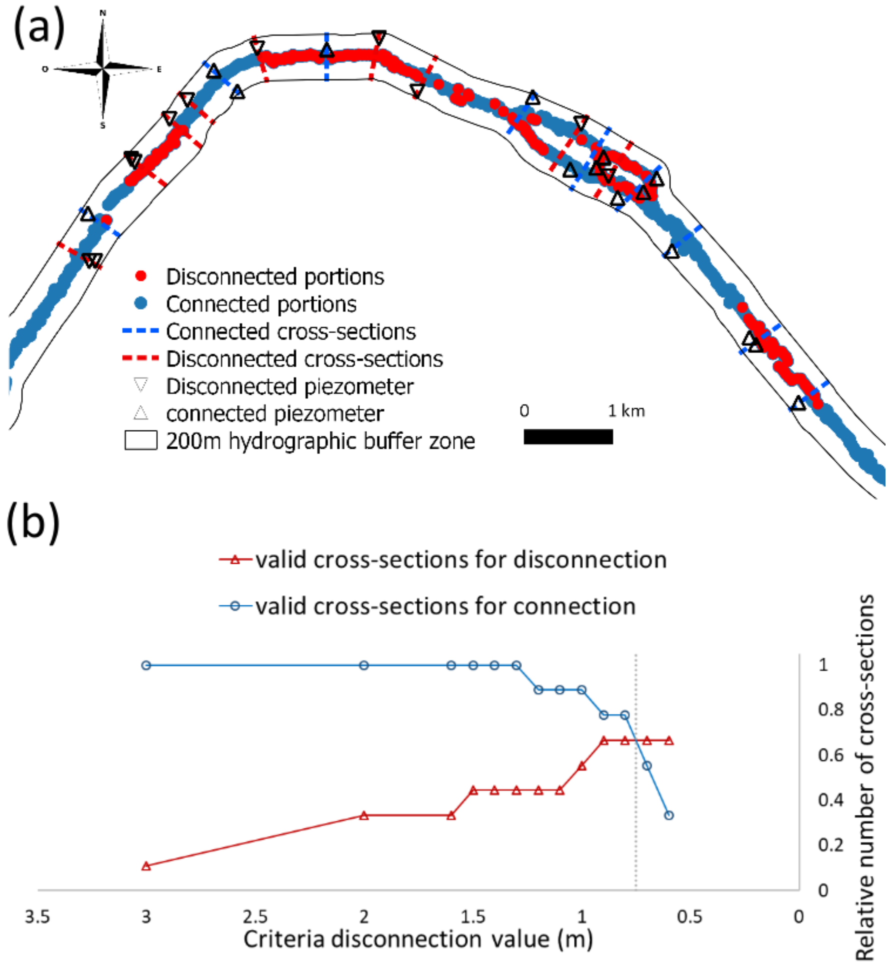

Figure 5. Graphical representation for disconnection criteria adjustment: (a) map of observed SW-GW status related to estimated SW-GW connection status using the optimal 0.75 m value for disconnection criteria; (b) Relative number of valid SW-GW connection status out of 9 disconnected cross-sections and 9 connected cross-sections.

Number: 1 Author: Subject: Highlight Date: 9/17/19, 12:29:19 PM

Please show either in figure 3, 6 or as an inset in this figure which reach of the river-aquifer system is being depicted in a.