Quali-quantitative considerations on low-flow well purging and sampling

Considerazioni quali-quantitative sullo spurgo e campionamento a basso flusso dei piezometri

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Riassunto

In questo articolo vengono trattati sia i principali vantaggi che le problematiche relative allo spurgo e al campionamento delle acque sotterranee solitamente effettuati con la cosiddetta metodologia a basso flusso o con il metodo dello spurgo di 3-5 volumi del pozzo, tutt'ora molto utilizzato nei monitoraggi ambientali.

Viene presentata una revisione della recente letteratura riguardante le caratteristiche tecniche, le innovazioni esecutive e la modellazione relativa al campionamento a basso flusso. L'obiettivo è quello di fornire al lettore una panoramica quanto più possibile vasta sugli studi effettuati e di offrire una visione nuova, che tenga conto di due aspetti:

1. L'aspetto qualitativo, relativo alla rappresentatività del campione prelevato attraverso un corretto spurgo del pozzo/piezometro di monitoraggio e quindi alla conseguente giusta interpretazione dei dati idrochimici;

2. L'aspetto quantitativo, relativo alla possibilità di sfruttare i dati piezometrici durante le operazioni di spurgo e campionamento a basso flusso per ottenere una stima della conducibilità idraulica orizzontale dei terreni, senza ulteriori indagini.

La metodologia di campionamento a basso flusso può, quindi, risultare molto vantaggiosa negli acquiferi alluvionali, fornendo campioni rappresentativi delle acque sotterranee e caratteristiche idrodinamiche dell'acquifero, con costi e tempi ridotti. Tali aspetti sono entrambi importanti nel contesto del monitoraggio ambientale di un sito potenzialmente contaminato.

Abstract

This article deals with both the main advantages and issues related to groundwater purging and sampling that are usually carried out through the so-called low-flow methodology or with the method based on the purging of 3-5 well volumes, which is still widely used in environmental monitoring.

A review of the recent literature concerning the technical characteristics, innovations and modelling related to low-flow sampling is presented.

The aim is to provide to the reader a broad overview on this specific field application and offer a new vision, which considers two aspects:

1. The qualitative aspect, relating to the representativeness of the sample taken through a correct purging of the monitoring well and the consequent correct interpretation of hydrochemical data;

2. The quantitative aspect, related to the possibility of using water level data during purging and low-flow sampling operations to estimate the soil horizontal hydraulic conductivity, without further investigations.

Low-flow sampling methodology can be very useful especially for alluvial aquifers, providing representative samples of groundwater and hydrodynamic characteristics of the aquifer, with reduced costs and times. These two aspects are both important in the context of an environmental monitoring plan for a potentially contaminated site.

Inroduction

Groundwater sampling guidelines, in Italy as well as worldwide, generally report that purging a well is mandatory prior to the sampling step (Kaminski 2006; Yeskis and Zavala 2002; Brodie et al. 2009; Rogers 2017; Weaver et al. 2007). This requirement is due to the aim of collecting groundwater samples that should be "as representative as possible" of the aquifer local conditions and not influenced by the casing storage. For this reason, researchers usually distinguish well water (stagnant) and formation water (flowing) (Barcelona et al. 1985).

The procedure and the threshold for a sufficient well purge are still today not fixed. The scientific debate is open, trying to assess if the stabilization of chemical-physical parameters (Table 1) or 3-5 well volumes purged is more effective.

Tab. 1 - Criteria for field parameter stabilization prior to sampling step (EPA/Cal-EPA).
Tab. 1 - Criteri per la stabilizzazione dei parametri di campo prima della fase di campionamento (EPA/Cal-EPA).

Parameter	Unit	Minimum
Temperature (T)	± 3% of reading (min ± 0.2 °C)	Cal-EPA, 2008
pH	± 0.1	EPA, 1996; Cal-EPA, 2008
Electrical Conductivity (EC)	± 3% of data	EPA, 1996; Cal-EPA, 2008
Redox Potential (ORP)	± 10 mV	EPA, 1996; Cal-EPA, 2008
Dissolved Oxygen (DO)	± 10% of data; 0.3 mg/l	EPA, 1996; Cal-EPA, 2008

A first distinction can be made: low-flow is mainly recommended for detecting constituents biased by turbidity and for high definition of contaminant distribution, whereas well volume is recommended when plume distribution and turbidity are not critical issues (Barcelona 1985; Kaminski 2006; Yeskis and Zavala 2002).

In Italy, current national legislation does not impose one specific practice and the Manual for Environmental Surveys in Contaminated Sites (ISPRA 2006), which is very detailed and published by the Italian Environmental Protection Agency (ISPRA), presents both as equally valid. A good sampling protocol for groundwater has been recently presented (Preziosi et al. 2016), but the difficulty of standardizing procedures in different settings and conditions is still evident in professional practice. In general, for low-flow purging, the stabilization order is: pH, electrical conductivity and temperature, followed by dissolved oxygen and redox potential (Preziosi et al. 2016). This assuming that instrumentation presents a good status of the electrodes (cleaning, conservation with suitable solutions provided by the manufacturer) and periodic calibration for a correct sampling operation is carried out.

Several works proved that the effectiveness of the purging procedure, even the "no purge solution" (Armstrong et al. 2020), depends on many specific factors, such as the type of chemical compound investigated (Molofsky et al. 2018),

screen length, hydraulic conductivity heterogeneity (Gomo et al. 2018), aquifer type, aerobic or anaerobic conditions (Bonte et al. 2017; Vroblesky et al. 2007), intake position, flow regime (Martin-Hayden et al. 2014). As regards the type of chemical compound, for example, "passive" samplers or "no purge" solutions proved to be more effective than low-flow purging for volatile organic compound (VOC), detecting higher concentrations and avoiding bias (Britt et al. 2010; Vroblesky et al. 2007). Similar results have been found for polyfluoroalkyl substances (PFAS) (Armstrong et al. 2020). Some authors tried to find the best parameter for assessing stabilization. Dissolved oxygen (Qi et al. 2017), and Radon-222 (Dehnert et al. 2020; Han et al. 2007) are the most promising. Anyway, each specific case should be studied prior to the adoption of a specific sampling method. Despite these uncertainties, low-flow technique (≤ 1 L/min) is widely considered and presented as the best well purging procedure due to repeated, consistent performances in several hydrogeological settings and for several analytes (Barcelona et al. 2005).

Moreover, unlike high-flow, the reduction of purged water volumes is a sensitive topic for businesses and field operators. This is also the reason why low-flow methodology has been increasingly used for several years (Schilling 1995). The best results, in terms of sampling representativeness and applications, have been obtained in alluvial aquifers, where the hypothesis of aquifer homogeneity is more easily respected and preferential paths are not frequent as in fractured formations (Barrez et al. 2007). Particular attention is to be paid to those cases in which the influence of vertical flow may occur (McMillan et al. 2014), but difficulties can be overcome by the use of numerical models before field monitoring activities (Harte 2017; Martin-Hayden et al. 2014; Varljen et al. 2006).

It is the authors' opinion that several studies, but also national technical guidelines, generally approaches to this theme only from a qualitative point of view. In a cost-benefit assessment of the different procedures, the single aim of obtaining a representative sample after a proper well purge may be not enough. A broader view, taking into account the following steps of a contaminated site remediation, could also consider the quantitative advantages obtained from the application of low-flow method. The abundance of hydraulic data (drawdowns), which can be collected during the procedure, can be used to determine aquifer properties, such as horizontal hydraulic conductivity (K_H), usually assessed with slug tests (Binkhorst and Robbins 1994). K_H can be easily assessed during low-flow conditions too, using water level data collected after the stabilization and following simple procedures of data processing, valid both for fully penetrating (De Filippi et al. 2020; Robbins and Higgins 2018; Robbins et al. 2009) and partial penetrating wells (Aragon-Jose and Robbins 2011). The evaluation of K_H through these methods is not always easily possible, especially in low-permeable layers, where drawdowns may be too high to fully respect Dupuit's assumptions for radial flow and to neglect well losses and turbulence, even in low-flow conditions.

Low-flow and Dupuit-Forchheimer assumptions

Dupuit-Forchheimer assumptions can be summarized as it follows:

1. The flow is horizontal at any vertical cross-section;
2. The velocity is constant over the depth;
3. The velocity is calculated using the slope of the free surface as the hydraulic gradient;
4. The slope of the water table is relatively small;
5. The well must be complete over the entire aquifer.

The 1st assumption implies that equipotential lines are vertical and leads to the 2nd one.

A steady-state groundwater flow is considered in (1), assuming that, at a specific distance (R) from the well intake, a virtual feeding drainage trench keeps the groundwater level (H) constant.

$$K = \frac{Q \cdot \ln\left(\dfrac{R}{r_w}\right)}{\pi \cdot \left(H^2 - h_w^2\right)} \qquad (1)$$

where:

Q = pumping rate (m³/s)
K = aquifer hydraulic conductivity (m/s)
R = influence radius (m)
r_w = radius of the monitoring well (m)
H = undisturbed water level in the monitoring well (m)
h_w = steady-state water level in the monitoring well (m)

In Figure 1, three simplified sketches of real cases studied during low-flow purging are reported (De Filippi et al. 2020). The screen length covers the entire saturated zone and the only simplification is layer homogeneity. For the typical range of low-flow discharges Q (0.1 - 1 L/min = 1.67×10^{-6}–1.67×10^{-5} m³/s), the assumptions are well-respected for K_H between 1×10^{-7} m/s and 1×10^{-4} m/s. For higher values of K_H, flowrate should be increased in order to notice an appreciable stable drawdown (Δh). The K_H thresholds may slightly depend on aquifer thickness that modifies the $\Delta h/H$ ratio.

Based on these data, for the application of methodologies that estimate K_H from low-flow water level measurements, alluvial aquifers are preferred. It should be noticed that the K_H obtained by the application of the method is someway an average value, coming from a weighted average of different soil layer properties along the screen length. In the same way, the error coming from the assumption of layer homogeneity may lead to misleading interpretations because water quality data derive from a permeability-weighted sample (Figure 2).

Sample origin is related to different factors (hydrogeology, well construction, pump intake) and its bias may be related to ambient vertical flow in the wellbore. Sometimes pumping rate should be higher than the usual of low-flow sampling in order to obtain a permeability-weighted sample. McMillan et al. (2014) presented a study where sampling bias is introduced by vertical flows and concluded that before the interpretation of sampling data supporting flow investigations are recommended.
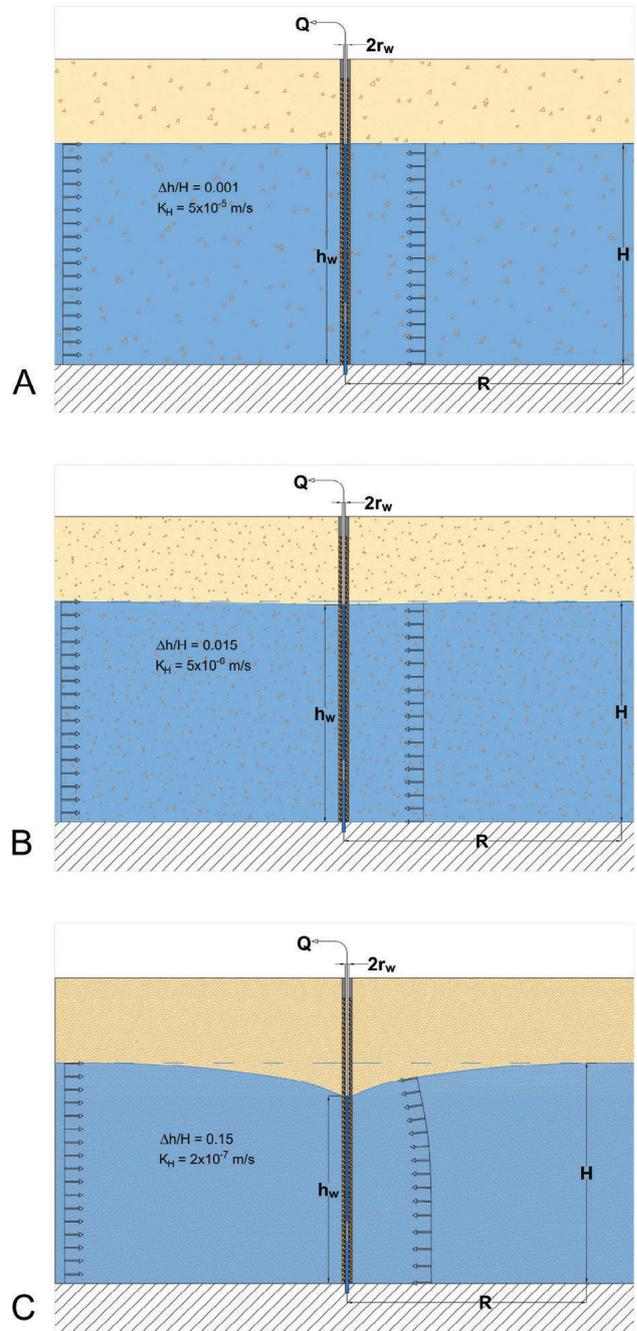

Fig. 1 - Measured drawdowns (Δh) in low-flow purging for aquifers with 3 different K_H (A, B and C).

Fig. 1 - Abbassamenti misurati (Δh) con lo spurgo in low-flow per acquiferi con 3 diverse K_H (A, B e C).
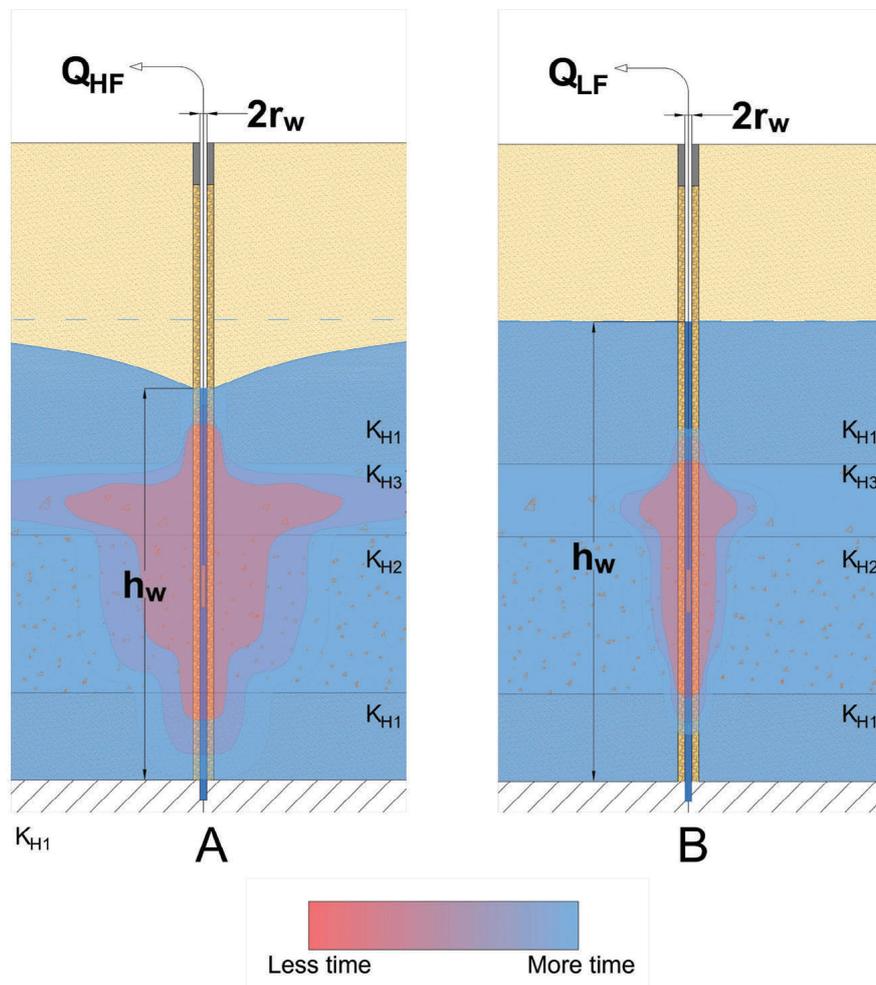
Fig. 2 - Sketch of sample origin at increasing high-flow (A) and low-flow (B) purging time in a multilayered aquifer ($K_{H1} < K_{H2} < K_{H3}$).

Fig. 2 - Schema dell'origine del campione per tempi crescenti durante lo spurgo ad alto flusso (A) e a basso flusso (B) in un acquifero multistrato ($K_{H1} < K_{H2} < K_{H3}$).

How the in-well flow may affect groundwater sample quality

The volume method of purging may lead to dewatering wells in soils characterized by low hydraulic conductivities. Most of water initially purged comes from the preexisting screen water and the water column above the screen (screen and casing water). The increase in groundwater velocity during the purge, related to the increasing hydraulic gradient, can cause turbulence near the well. Increases in velocity and turbulence, relative to the natural groundwater conditions, may cause dissolved oxygen (DO) variations (with chemical reactions triggered) and mobilization of soil particles and/or colloids that would not otherwise be moving under natural groundwater seepage gradients (Menz 2016; Harte 2017; Sevee et al. 2000). Hence, turbulent flow may lead to a significant loss of volatile contaminants, affecting water chemistry. This is often due also to the presence of low-permeability layers.

Nevertheless, what does it mean "low", practically? Actually, these effects (vertical gradients, turbulence, clogging, a non-stabilized drawdown) could be noticed also during a low flow purging in very-low K_H formations (i.e. $< 10^{-7} – 10^{-8}$ m/s). The stabilization of water level and physical-chemical parameters is not ensured simply by reducing the flowrate within the usual range from 0.1 to 1 L/min ($1.67 \times 10^{-6}–1.67 \times 10^{-5}$ m³/s). A flow rate could be too high for some formations (silt with clay) or too low for others (coarse sand and gravel). It is the minimized drawdown, rather than the flowrate, that reflects the interaction between purging flow and the hydrodynamic characteristics of the aquifer. Drawdown should be checked continuously because it represents the aquifer's response to the imposed external stress. It suggests the first indication for "proper" flow conditions occurring nearby the well prior to sampling. This is a further confirmation that the approach to these operations must both qualitative and quantitative.

Several authors, investigating the low-flow methodology with different models (both analytical and numerical), tried to assess the groundwater sample representativeness and evaluate the optimal purge duration in the most varied circumstances (Harte 2017; Mcmillan et al. 2015; Qi et al. 2017). Qi et al. (2017), considering both screen water and formation water as representative, reached a fraction of 97% in only about nine minutes of purging (red line in Figure 3). However, excluding screen water as representative, the required purge time prior to sampling would become 20 minutes or more, which is actually similar to the results presented by McMillan et al. (2014) and Harte (2017). McMillan et al. (2014) proposed a
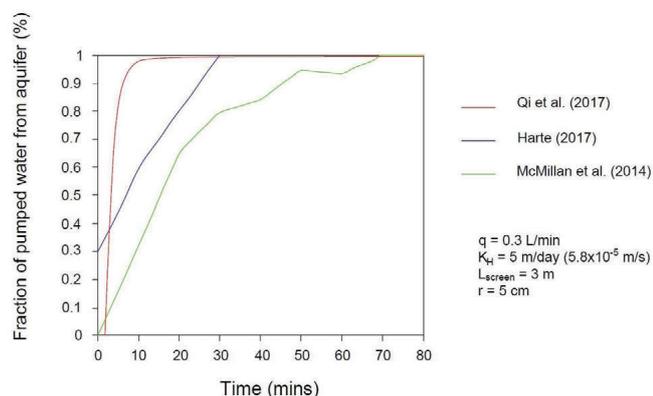
Fig. 3 - Low-flow sampling representativeness. Comparison between solutions obtained by different models of three recent research studies is showed.

Fig. 3 - Rappresentatività del campionamento a basso flusso. È rappresentato un confronto tra le soluzioni ottenute da diversi modelli proposti da tre recenti studi scientifici.

numerical model, accounting also for partial penetration, vertical flow and casing storage, whereas Harte (2017) presented a simple analytical model which also provided K_H values averaged over the screen interval, with a fixed radius of influence R of 10 ft (about 3 m).

All these results suggest that the most challenging issues in low-flow sampling and purging are vertical flows occurring in well screen, mostly due to the pump intake coincident with low K_H layers or simply to a significant heterogeneity along the screen.

Hydrogeological heterogeneities highly influences sampling results. Hence, it is a question of setting the right flow rate for the specific aquifer, controlling the drawdown. This is why low-flow rate usually matches with porous aquifers, with K_H values between 10^{-7} and 10^{-4} m/s. For very-low K_H formations ($< 10^{-7}$ m/s) one has to be very careful with sampling flowrates and it might be even more useful to use a passive sampler, assuming a well water in chemical equilibrium with the aquifer, but neither three volumes purged nor parameters stabilization would be respected. In these cases, even using low-flow, it could take many hours of purging prior to sample groundwater that is for a 50% coming from the screen and only 50% from the aquifer (Sevee et al. 2000) or even less (McMillan et al. 2014). Martin-Hayden et al. (2014), for instance, found that purging at least two screens volume is required to obtain a sample consisting of 94% formation water. For this reason, some authors proposed to combine low-flow and volume methods in a new high stress low-flow (HSLF) sampling approach. An initial high-flow rate of pumping is followed by a low-flow rate for purging and sampling steps, to both reduce purging time and preventing the downward movement of the stagnant water (Wang et al. 2019).

Conclusion

The low-flow methodology is widely used all over the world for purging and sampling operations. It is not recommended for organic compounds, but it generally allows to reduce purged water volumes and their disposal. Flow investigations are necessary prior to sampling operations, for a correct interpretation of qualitative data obtained from low-flow sampling. Sometimes flow-rates might be set higher than usual range considered, due to specific hydrogeological settings related to high hydraulic conductivity aquifers. Obtaining a formation water sample is the main objective, but it should be considered that it will be a permeability-weighted sample and the knowledge of hydrogeological context is essential.

In addition to the aim of maximizing representativeness of groundwater samples, one of the major strengths of low-flow method is also the possibility of having for each monitoring well a small-scale aquifer test and obtaining hydrogeological parameters without any additional site investigations (i.e. slug tests). This advantage reduces costs and times in a groundwater-monitoring plan related to a potentially contaminated site, often located in areas around old closed landfills characterized by alluvial aquifers.

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