Acque Sotterranee - *Italian Journal of Groundwater* (2023) - AS44-656: 63 - 73

DOI 10.7343/as-2023-656

Nota Tecnica - Technical Note

not peer reviewed

Water well drilling: tips and key points to consider in water well design

Perforazione di pozzi per acqua: consigli e aspetti chiave da considerare nella progettazione di pozzi per acqua

Alessio Fileccia - Geologo professionista - email: *studio@filecciageologia.it*

Riassunto

Migliaia di pozzi sono perforati ogni giorno per estrarre acque sotterranee utili ad una gran varietà di scopi. In molti casi questi pozzi vengono posizionati con una conoscenza scarsa o nulla del sistema acquifero da sfruttare. Purtroppo questa pratica, normale in molti paesi del terzo mondo, lo è talvolta anche in Europa. Gli esempi degli impatti ambientali che ne conseguono sono presenti nella letteratura scientifica: da miscelazioni accidentali di acque provenienti da acquiferi diversi, a pericolosi fenomeni di subsidenza del terreno, al prosciugamento di corpi d'acqua superficiali e sorgenti. Questo breve articolo illustra le fasi più importanti che dovrebbero sempre accompagnare la ricerca e l'utilizzo di acqua sotterranea mediante pozzi. L'argomento è noto e descritto in molti altri testi del settore, ma l'autore ritiene comunque utile fornire un contributo riportando alcuni casi tratti dalla propria esperienza professionale. L'articolo descrive alcune importanti procedure che dovrebbero sempre fare parte della progettazione di ogni pozzo per acqua, qualunque sia il volume da estrarre. L'argomento è descritto in tre capitoli principali: 1) perché sono necessarie le indagini preliminari e quali sono gli effetti negativi che si possono prevedere attraverso queste; 2) quali sono gli specialisti principali coinvolti in questo genere di studi; 3) quali sono i compiti principali dell'idrogeologo. L'esposizione è corredata da figure con didascalie chiarificatrici e da una utile bibliografia di base.

Abstract

Thousands of water wells are drilled every day to abstract groundwater for a range of purposes. These wells are frequently sited and designed without adequate knowledge of the local hydrogeology and the targeted aquifer. Unfortunately, uninformed well siting and design is a common practice not only in Europe but also in many developing countries. The practice can not only jeopardize basic well function but also lead to a number of widely cited consequences to the environment, such as, undesired aquifer water mixing, hazardous soil subsidence, and the drying up of surface water bodies or springs. This brief paper highlights the key groundwater investigation procedures for more informed well siting and design to help mitigate against undesired environmental consequences. The subject has been discussed in recent literature, however this paper contributes practical insight based on the author's real-world experience that may be valuable to the practitioner. The paper describes important procedures which should always be part of any water well project, regardless how much water is to be extracted. The paper addresses three issues critical to siting and designing wells: 1) the need for preliminary investigations and potential environmental impacts 2) the key experts that should be involved in these investigations; and 3) the core tasks of the hydrogeologist. Explanatory figures and references are given.

Keywords: *hydrogeological conceptual model, screens, cementation, aquifer test, drilling specifications.*

Parole chiave: modello idrogeologico concettuale, filtri, cementazione, prove di pompaggio, specifiche di perforazione.

Foreword

The planning and design of a new water well requires a certain number of preliminary investigations regardless of the volume of water to extract from the aquifer (Brassington, 2007; Freeze & Cherry, 1979; Kasenow, 2001).

This paper highlights the importance conducting a baseline study when planning the drilling of a water well.

Practically speaking, groundwater exploitation can be seen as a compromise between the requirements of the client, the expertise of the drilling contractor and the availability of the local water resources. Generally most owners and clients of a new water well are seeking two basic outcomes:

- A reliable and sustainable supply of clean freshwater and
- Minimal construction, operation and maintenance costs.

Less obvious to many clients is the impact that drilling their new well may have on the local environment or on other wells in the vicinity. Indeed most clients are likely unaware that installing their new well could, over time, adversely affect chemical conditions or discharge of the local aquifer or even violate local environmental regulations. This paper offers examples of both good and bad practices for clients who must make decisions regarding the drilling of a new borehole for groundwater extraction. For a more thorough overview of drilling operations, drilling permits, extraction permits or health and safety regulations for building water wells, the reader is urged to consult the references provided herein. The reader should also be familiar with hydrogeological terminology (Heath, 1983; Kresic, 2007). A recommended guideline is this groundwater glossary (https://www.groundwater.org/get-informed/basics/glossary.html - The Groundwater Foundation).

The text is divided into three main chapters:

1. why preliminary investigations are necessary and the adverse impacts they could help forecast;
2. the key experts that should be involved in these investigations and
3. the core tasks of the hydrogeologist.

The author is aware that the topic is described in many other papers and reports (some of which are listed in the references), but he wishes nonetheless to highlight some of the main pitfalls that are often encountered in order to encourage best practice

DOI 10.7343/as-2023-656

Water well preliminary investigations and specifications

For centuries mankind has understood that certain types of rock can host significant amounts of clean safe-to-drink groundwater and that under certain situations groundwater can naturally flow to surface. A water well is essentially a vertical hole in the ground that is made to stop when it encounters a porous saturated rock. When groundwater does not naturally rise to the surface, well engineers use a variety of ways to pump it out, either by hand, wind power, solar power, electric power, etc.

Broadly speaking a correct drilling procedure involves:

- siting the borehole in a suitable environment, to avoid interfering with other pumping wells and to avoid having any unwanted impact on the aquifer, which could occur after a short period of operation, both quantitatively and qualitatively;
- more specifically the water abstracted from the new well must allow for a safe yield for the aquifer, the surface ecosystem and the required volumes for the community; the resource should have adequate annual recharge and drawdowns must be able to recover easily (without approaching to a tipping point); the pumped discharge must be adjusted to account for unexpected periods of low precipitation that may arise;
- the well itself should be operated and routinely maintained for a considerable period of time (years) in order to minimize the clogging of the filter or corrosion that can result from certain aquifer chemistries. The design and the development of a successful water well, planned to last for years, relies on a set of additional crucial steps (Misstear, 2006):
  a. conducting a baseline study of the groundwater occurrence, aquifer geometry, water quality, potential pollution sources;
  b. locating a suitable borehole site;
  c. selecting a suitable type of well or borehole, and designing the installation;
  d. constructing the well or borehole and identifying its stratigraphy (eg. well log);
  e. testing the well performance and determining the aquifer properties;
  f. testing the groundwater quality (chemistry);
  g. monitoring and maintaining the well and rehabilitating or decommissioning it when necessary;
  h. planning a roadmap for the well maintenance service.

Based on the three primary subjects mentioned above the following gives some necessary operational activities.

a. **Aquifer assessment and approximate geometry**. The area of intervention must be investigated and studied to reconstruct a simplified geological and hydrogeological model. The model should be capable of describing the important underground and surface features such as: type and lithology of the aquifer and surrounding formations, their top-bottom depths and the recharge and discharge areas etc. (Fig.1) (Kresic & Mikszewski, 2013).

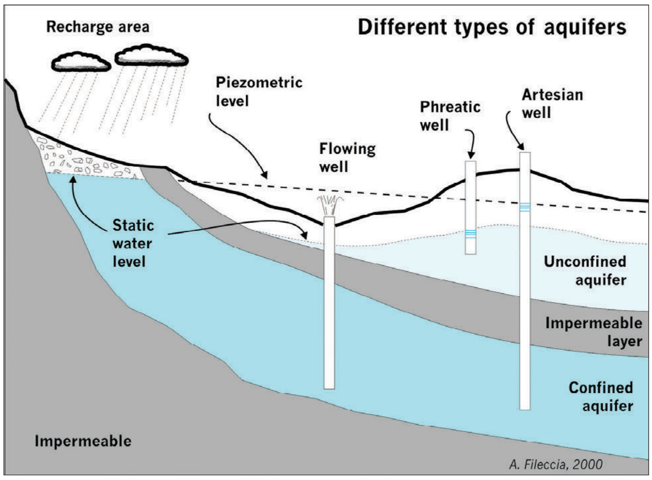


Fig. 1 - I principali acquiferi sotterranei (confinati, liberi).

Fig. 1 - General classification of aquifers (confined, unconfined).

Aquifer hydraulic conditions are generally defined as (Freeze & Cherry, 1979):

– Unconfined or water table aquifers, in contact with atmospheric pressure,
– Confined, trapped between two impermeable layers,
– Semi-confined, when the top layer is not considered to be completely impermeable but has a very diminished hydraulic conductivity.

The siting of the new well should therefore be made on the basis of a properly constructed geological and hydrogeological conceptual model which identifies, for example, geometry of the aquifer and its top and bottom horizons (Fig. 2).

Available groundwater resources compared to the environmental receptors and the required abstraction should be investigated performing a groundwater balance of all possible natural and artificial contributing factors (inflows and outflows). This practice helps to prevent undesired consequences such as the drying up of surface water bodies or surrounding wells. The general approach is, essentially,

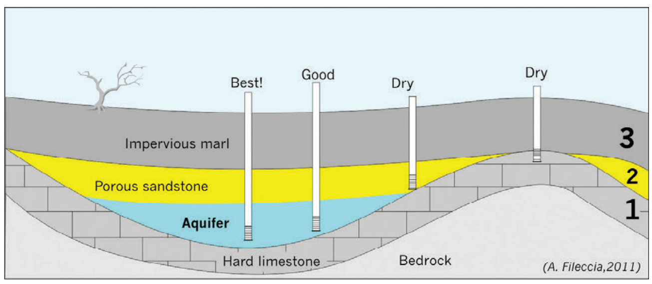


Fig. 2 - Un corretto posizionamento del pozzo aiuta a risparmiare tempo e ridurre le spese a lungo termine. La figura mostra quattro pozzi posizionati in diversi punti. I due a destra sono stati ubicati dopo una indagine geologica approssimata od assente, mentre i due a sinistra dopo un'indagine accurata coadiuvata dalla geofisica. Nel secondo caso è stato possibile individuare meglio la geometria dell'acquifero e quindi la sua parte più profonda, ubicando i pozzi nella zona più produttiva.

Fig. 2 - A correct siting of the water well helps saving time and money in the long run. The figure shows different sites of four different water wells. The two on the right were sited without or with insufficient, preliminary geological investigation, while the two on the left were sited after a geological/geophysical survey that enabled the deeper part of the aquifer, to be identified and hence sited in a more favorable position.

Acque Sotterranee - *Italian Journal of Groundwater* (2023) - AS44-656: 63 - 73 DOI 10.7343/as-2023-656

to design the well to produce a volume corresponding to the yearly natural fluctuation of the water table. This process is based on the false assumption that the water table reaches the same level year after year. Many have demonstrated that this assumption is incorrect (Alley, Reilly & Franke, 1999; Franke, Reilly, Pollock & LaBaugh, 1998) and does not take into account the water volumes required by the natural environment, normally hidden and difficult to extrapolate from the balance calculations. In reality the determination of the actual exploitable resources, requires extensive investigations and, when there is any uncertainty a safe protocol is to design the well to withdraw less than the estimated annual groundwater fluctuation as a highest value (Fig. 3). Based on the author's experience one-to two-thirds of the mean annual effective recharge is an optimal place to start for designing well productive rates.

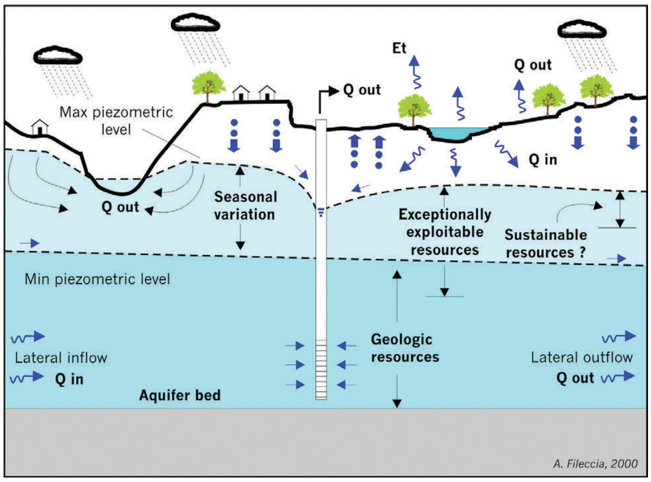


Fig. 3 - Ricostruzione semplificata di un acquifero freatico, dei flussi in entrata ed uscita e della risorsa sostenibile. L'approccio usuale, ancora adottato oggi in molti paesi, è quello di pompare dei volumi idrici che corrispondono all'incirca a quelli delle variazioni piezometriche annuali. In questo modo non vengono considerate le quantità utilizzate dall'ambiente (copertura vegetale, aree paludose, fiumi, ecc.) Nel lungo termine questo porta ad effetti indesiderati e ad abbassamenti di falda difficilmente recuperabili (USGS, 1999; Freeze, Cherry, 1979)

Fig. 3 - Simplified reconstruction of a water table aquifer with its major inflows and outflows and sustainable resources. The normal approach, still in use today and in many countries, is to pump out water volumes corresponding to the mean annual water table fluctuation. By doing this, we do not take into consideration the part of the water allocated to the environment (vegetation, marshlands, rivers etc.). In the long term, this will lead to undesirable results together with a non-recoverable drawdown (USGS, 1999; Freeze, Cherry, 1979).

b. Another major point in support of an exhaustive knowledge of the local hydrogeology is **the sequence stratigraphy and the hydraulic levels of different aquifers**.

This may influence the selection of the well design and particularly that of cementation (sealing).

Cementation or isolation, must be a common practice to avoid mixing of aquifers with distinct piezometric levels encountered during drilling, see Figures 4-5, (Kresic & Mikszewski 2013; Driscoll, 1986).

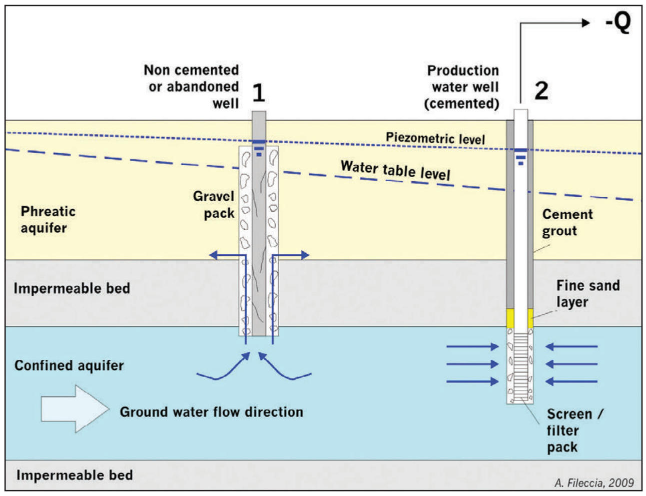


Fig. 4 - Per evitare un mescolamento tra acquiferi con diversi carichi idraulici, o l'inquinamento di un acquifero confinato dalla superficie, una procedura normale è quella di isolare tramite cementazione la falda superiore. Il flusso idrico può subire modifiche durante i diversi regimi piezometrici annuali e, ad esempio, se il livello piezometrico è più basso di quello freatico il flusso procede dal pozzo abbandonato (1) all'acquifero confinato.

Fig. 4 - To avoid an unwanted mixing between aquifers with different hydraulic heads, or the pollution of a confined lower aquifer from above, a common procedure is to isolate (sealing by cementation) the upper water table. During different regimes the vertical flow can be reversed such as when the piezometric level is lower than the water table, the flow is from the abandoned well, 1, to the confined aquifer.

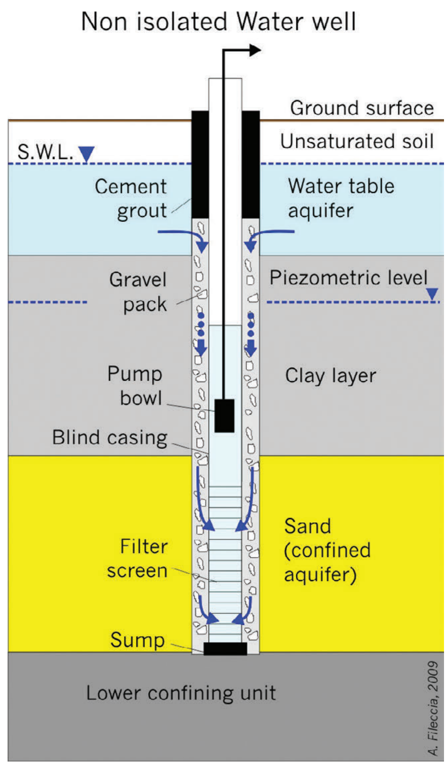


Fig. 5 - Quando il pozzo è filtrato per quasi tutta la sua lunghezza, si stabilisce una comunicazione idraulica tra l'acquifero superiore e quello inferiore confinato. Il semplice modello costruttivo favorisce il trasferimento veloce in profondità degli inquinanti attraverso un mezzo a permeabilità maggiore (dreno artificiale) verso l'acquifero sfruttato e naturalmente protetto in origine.

Fig. 5 - When the well has a gravel pack all along its length, communication from the surface is permitted to the aquifer and the underlined confined aquifer. The poor well design leads to pollutants seeping deeper and faster through a higher permeable medium (artificial drain) into resource aquifer that was naturally shielded from contamination.

DOI 10.7343/as-2023-656

c. Determine the average discharge rate and the pump capacity and pump type for the well.

One common question regarding the design of the well is related to the selection of the proper hole diameter. Hole diameter will determine the size of casing and the diameter of the pump that are needed along with the pump capacity. The volumes delivered are generally submitted in units of L/s or m^3 /hr. Table 1 provides a guideline for the selection of the casing diameter based on the required discharge Driscoll 1986; Sterrett, 2007).

Tab. 1 - Diametri del rivestimento e della pompa consigliati per ottenere un dato valore di portata.

Tab. 1 - Recommended casing diameter and pump diameter corresponding to required discharge.

Discharge rate (m^3 /s)	Discharge rate (L/s)	Optimum casing diameter (cm)
<0.006	< 6	15,24
0.005-0.011	5 - 11	20
0.009-0.022	9 - 22	25,4
0.018-0.044	18-44	30,48
0.03-0.063	30-63	35,56
0.05-0.11	50-110	40,64
0.075-0.18	75-180	50,8
modified from Driscoll, 1986		

Another element to account for is the total piezometric head necessary to rise the water up to the vertical borehole against gravity, often much higher than the ground surface. It is important to note that increasing the diameter of the hole/casing does not necessarily result in an increase in the volume of water pumped out. See example in Figure 6 obtained by applying Thiem equation.

As shown in Figure 6, doubling the diameter one only gets an increase of 12% of the discharge.

This must be carefully accounted for, considering the increase of the overall budget.

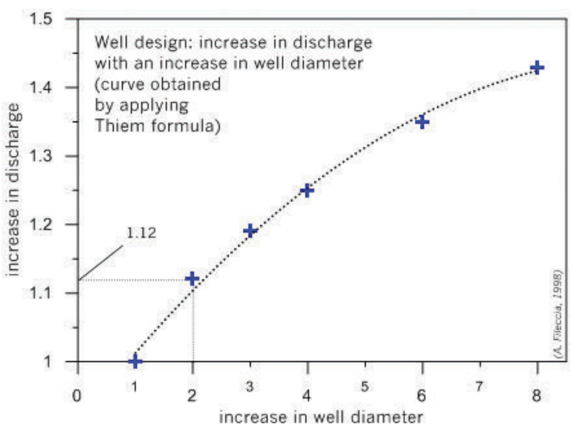


Fig. 6 - Relazione tra il diametro del rivestimento e la portata estratta. Raddoppiando il diametro, linea orizzontale, la portata aumenta solamente di 1,12 rispetto a quella iniziale.

Fig. 6 - Relation between casing diameter and discharge. Doubling the hole diameter, on the horizontal line, only contributes to an increase of 1.12 the original discharge.

d. The screen selection

Aquifers typically include fine particles, and removing these is crucial to protecting pumps and ensuring high quality water. Fine sand or silt can be blocked by using the correct filter screen and a gravel pack. The screen is commonly composed of iron or steel and has specialized slots designed to filter out finer sediment particles. Screens are not designed to exclude the finest material; instead this task is a task performed by an artificial gravel pack and /or the coarser grains of the aquifer after the development of the well (Fig. 7).

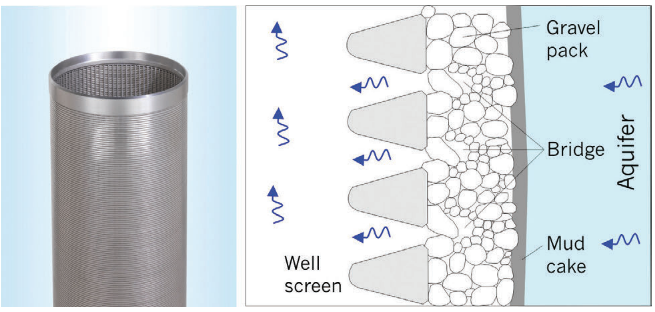


Fig. 7 - Filtro tipo Johnson (sinistra). Effetto ponte dovuto ad un corretto dreno artificiale (destra). Le finestrature (in grigio) hanno un'apertura più piccola sul lato verso il dreno per ridurre la possibilità di ostruzione da parte di particelle fini.

Fig. 7 - Johnson type filter screen (left). Bridge effect due to a correct artificial gravel pack (right). The screen slots (grey) have a smaller inlet towards the pack to prevent fines entering into the well.

Screens are usually defined by the amount of open space they contain in their openings. Table 2 illustrates several screen types, their slot sizes and the proportion of open space (density). The screens that are most effective have a higher percentage of open space and must be placed in front of the thicker aquifer interval.

According to Driscoll (1986) the size of the slots in screens should ideally retain 40% of the aquifer material, but alternative guidelines can be found in the literature (Driscoll, 1986).

The proper gravel pack can be selected using a variety of methods.

All of them are empirical and based on the experience of different drilling companies and researchers.

Choosing the correct gravel pack can be based on a sieve analysis of the aquifer material and the computation of the uniformity coefficient ($U = D_{60}/D_{10}$). The final goal is to install a pack comprised of rounded grains that has a permeability greater than the aquifer while yet having the ability to retain the finer material. The simplest case is that of a uniform, well graded, aquifer with $U < 3$.

In this case the gravel pack must have a value of U less than 2.5 and a value of D50 around four to six times the d50 value of the aquifer. So in the end, the expected well capacity is the parameter that defines the last drilling diameter that is sufficient to accommodate the required screen and gravel pack (Misstear, Banks, Clark, 2006).

Tab. 2 - Aperture in percentuale per diversi filtri. Un filtro a luce continua di 10,16 cm di diametro con aperture di 1,52 mm ha una superficie filtrante del 52% paragonata al 12% di un filtro a ponte.

Tab. 2 - Percentage of open area for different screen types. A 10.16 cm diameter continuous slot screen with 1.52 mm apertures has 52% of porosity compared to 12% for a bridge slot screen.

Screen diameter ID				**Filter type and percent open area**					
in	**cm**	**Slot size ***	**Slot size (mm)**	**Continuous slot, % of open area**	**Louvered %**	**Bridge slot %**	**Slotted pipe %**	**Plastic continuous %**	**Slotted plastic %**
4	10,16	20	0,5	25	-	-	-	13	-
		60	1,52	52	-	12	5	30	11
8	20,3	30	0,76	25	-	-	-	18	8
		60	1,52	41	3	6	5	29	14
		95	2,41	51	5	-	7	-	-
12	30,48	30	0,76	16	-	3	-	-	-
		60	1,52	28	4	7	5	-	11
		95	2,41	38	7	-	7	-	-
		125	3,17	45	9	14	9	-	-
16	40,64	30	0,76	16	-	3	-	-	9
		60	1,52	28	4	6	5	-	-
		95	2,41	38	6	-	7	-	-
		125	3,17	45	8	13	9	-	-
** the slot opening designates the slot width in thousandths of an inch (10 is an opening of 0.01 in or 0.25 mm)*									
modified from Groundwater and wells, 2007									

e. Adverse effects on surrounding boreholes.

After the pumping process begins the sudden drop in pressure causes a cone of depression due to the aquifer water entering the screen. As the cone grows over time, the increased (sometimes reversed) gradient can force lateral flowlines to be diverted towards the pumping well. As a result a zone of capture forms (Franke, Reilly, Pollock & LaBaugh, 1998;). The zone is a 3-dimensional volume with flowlines converging towards the well. The extent of the capture zone is influenced by several factors such as piezometric gradients, transmissivity, pump discharge etc. It has the potential to divert the path of some unwanted pollutants or merely reduce the discharge of other nearby wells (Fig. 8).

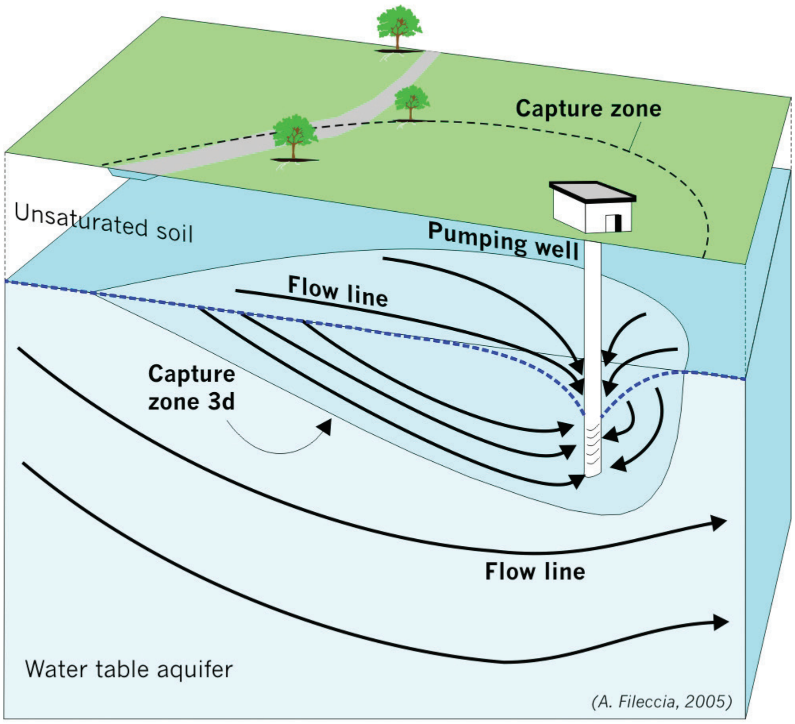


Fig. 8 - Zona di cattura attorno ad un pozzo. Il disegno evidenzia la curvatura delle linee di flusso vicino ai filtri, quando la pompa è in funzione. La pressione ridotta ed il cono di influenza possono avere due effetti negativi: una riduzione di portata estratta nei pozzi vicini e/o l'ingresso di acque inquinate esterne.

Fig. 8 - Capture zone around a pumping well. The sketch highlights the bending of the flow lines while approaching the water well screens, when pump is operating. The reduced pressure and the cone of influence may have two main adverse effects: a reduced discharge for the neighboring wells and/or the capture of polluted water.

DOI 10.7343/as-2023-656

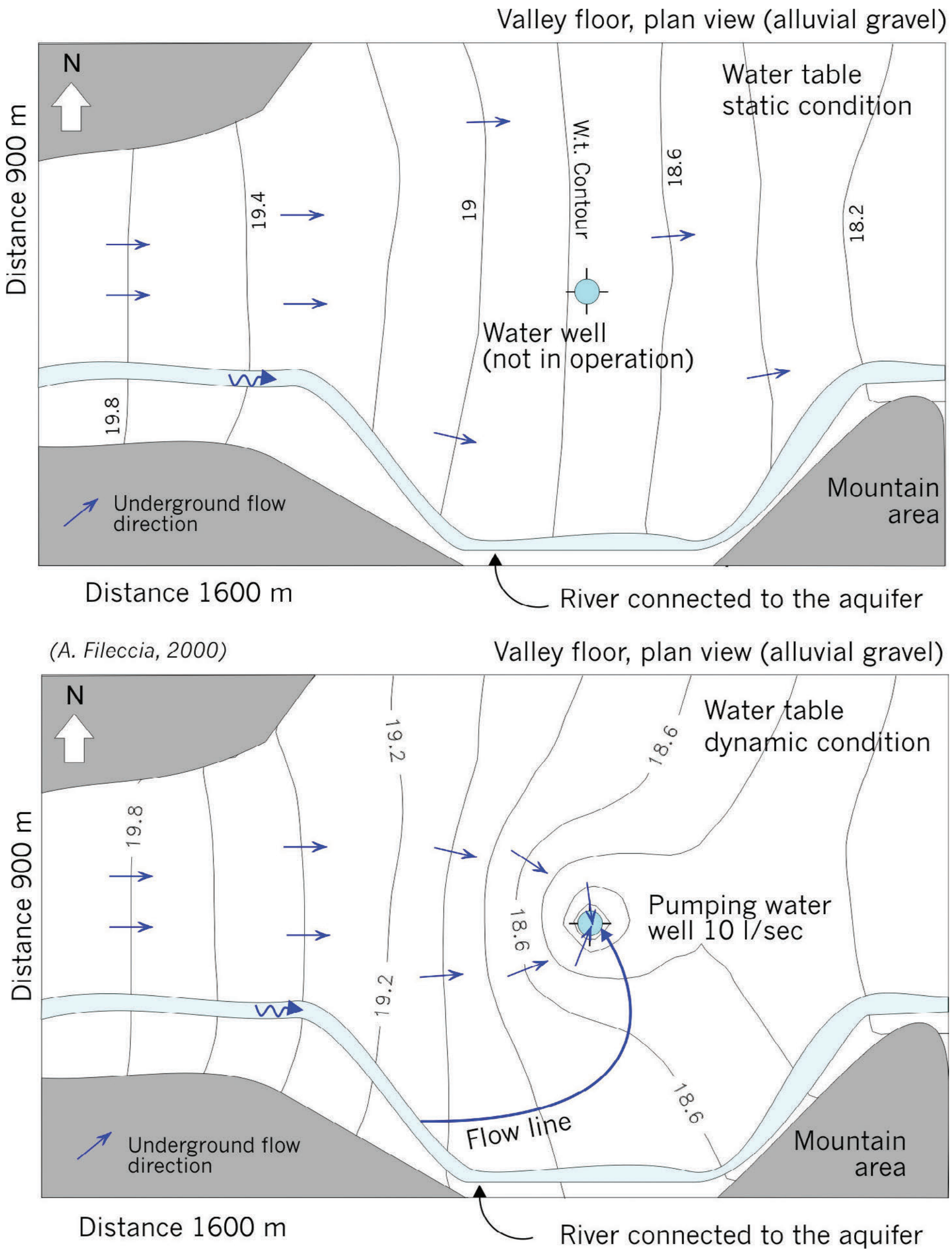


Fig. 9 - Esempio ricavato da un modello numerico che simula la deviazione delle linee di flusso causata da un pozzo in pompaggio a 10 L/s. In alto: in condizioni naturali il fiume sembra non essere collegato idraulicamente con l'acquifero. Le linee di flusso sono parallele al fiume. In basso: quando il pozzo inizia ad estrarre acqua si produce un cono di influenza che si espande fino al fiume, rivelando una possibile comunicazione.

Fig. 9 - Example derived from a groundwater model simulating the flow lines diversion due to the pumping well in the center of the plain at 10 L/s. Top: under natural conditions the river appear to not be hydraulically connected to the aquifer. Aquifer streamlines are parallel to the river. Bottom: a likely connection may be revealed by the cone of influence due to pumping.

f. **Another common implication due to pumping is the increased capture** (Fig. 9).

In the example given the well is withdrawing from the river and the water quality delivered from the supply station is influenced by that of the river (Fileccia, 2015).

For more information on this topic refer to the instruction manual and related software WHAEM from EPA.

g. **Example of a well design.**

After completing the hydrogeological conceptual model and performing a risk assessment, the hydrogeologist prepares a preliminary design of the water well (Fig. 10).

A well design includes a choice of the well's diameter, total depth of the well, screen or open hole sections, gravel pack thickness and a method of construction.

The pumping rate determines the pump size, which in turn determines the well diameter.

Manufacturers of well pumps typically provide information on the optimum well diameter and size of pump bowls for several anticipated well yields. The drilled hole at any depth should have a minimum diameter about 5 cm greater than

Acque Sotterranee - *Italian Journal of Groundwater* (2023) - AS44-656: 63 - 73 DOI 10.7343/as-2023-656

the outer diameter (OD) of the casing and screen string, although larger clearances are needed for grouting operations and installing a gravel pack.

For grouting, the National Ground Water Association (NGWA, 1998), for example, recommends an annular clearance of at least 5 to 10 cm between the casing and hole wall.

By doing so borehole's diameter is always greater than the screen OD in order to accommodate an artificial sand or gravel pack that should be at least 5 - 7 cm thick. Additionally the diameter of the intake pump and bowl should be taken into consideration when determining how much water need to be pumped. To reduce turbulence a clearance of 5 - 6 cm between the internal casing and the pump is recommended (Driscoll, 1986; Misstear, Banks, Clark, 2006; Sterrett, 2007)

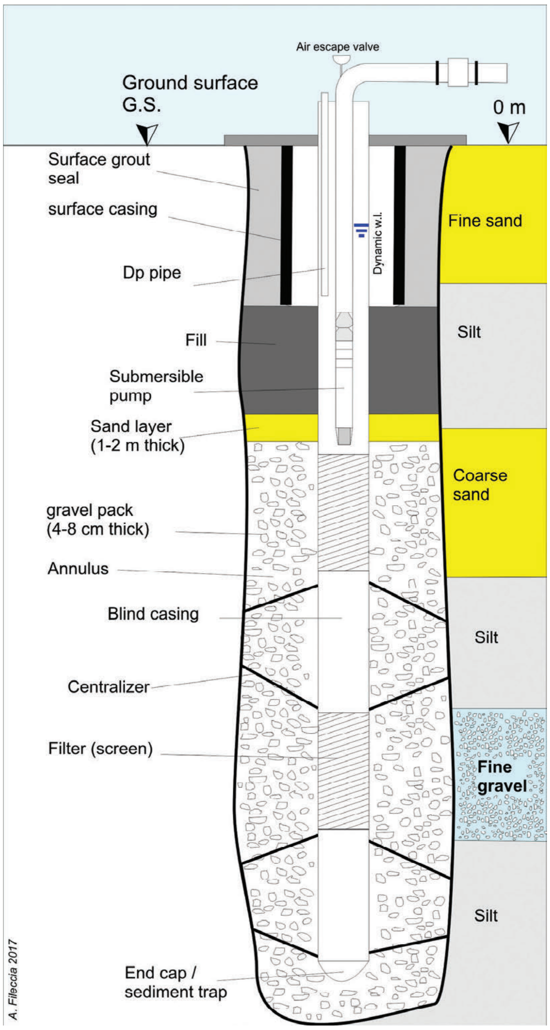


Fig. 10 - Disegno di un pozzo basato sulla litologia. Alcuni aspetti importanti: l'isolamento superficiale per evitare l'inquinamento dalla superficie; i filtri sono davanti ai livelli più permeabili; il dreno in ghiaia è per ridurre l'ingresso delle particelle più fini; i centralizzatori mantengono allineata la colonna, evitando che tocchi le pareti; il gruppo motore della pompa è posizionato al di sopra dei filtri; il tubo guida protegge la sonda multiparametro od il freatimetro.

Fig. 10 - Well design based on the local lithology. Some important features are outlined such as: the surface seal to prevent pollution; the screens in front of the more permeable levels; the gravel pack to reduce silting; the centralizers to keep the casing straight not touching the walls; the pump bowls just above the screen; the dip pipe to protect the water level meter or transducer.

h. Laws and regulations in effect

Many countries have specific regulations to follow when drilling and constructing new boreholes and disposing of mud debris. A proper procedure substantially helps in preventing future liabilities of litigations with nearby landowners or a regulating authority. The hydrogeologist must be aware and comply with the prevailing rules and clearly communicate to the client the risks of not being compliant.

i. Fact sheet and database compilations

Two straightforward but occasionally overlooked steps are the completion of a field form with pertinent well information detailing position, well head design, stratigraphy, chemical and hydraulic properties and the updating of a regional database. A borehole database (DB) is of enormous value to any situation enabling conceptual models of the aquifer system to be constructed. This phase has been demonstrated especially with little data and when aquifers are anisotropic like in crystalline fractured rocks. A thorough DB can provide a better description of the likelihood that a new well would produce the specified discharge under these specific circumstances

To be of some use the DB must be built on a consistent set of records. However extensive studies have shown that hydrogeological properties generally decline with depth (Fig. 11A-B)

There are in fact, a few unusual instances of greater yielding wells, even though aquifers in fractured crystalline rocks have poor transmissivities with depth, accounting for less than 1 L/s and under various latitudes. This progressive reduction has been statistically demonstrated by many authors (Bonsor, MacDonald, 2010; Gustafson, 2002). High yields in fractured, crystalline or metamorphic rocks, occur where there is a combination of favourable conditions for groundwater storage e.g. coarse and thick saprolite or alluvium overlying the basement with high aquifer transmissivities, expansive drainage basins, and well-developed fracture network (coincident lineaments) (Maurice at al., 2018).

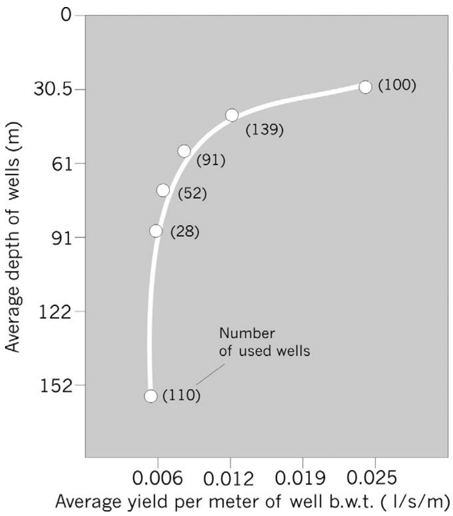
Which are the main experts involved for scheduling and coordinate these investigations?

The process of drilling a water well involves a number of experts who must work together at all times. Typically, a private owner, a community, an industry association, or a water supply body will submit the initial request. The main professionals typically encountered in the well drilling sector include:

- The drilling contractor
- The hydrogeologist
- The hydraulic engineer

Very often the client seeks to hire a drilling contractor, who typically takes care of the whole well siting, design and drilling process and has a hydrogeologist and hydraulic engineer on staff. When the water delivered does not meet the specified volumes, local regulations are not followed, or simply when consequences similar to those shown in the preceding figures occur, this could result in unanticipated outcomes or

DOI 10.7343/as-2023-656



Decrease in well yields with depth in crystalline rocks.
The curve shows that fractures in crystalline rocks decrease with depth due to the overlaying rock mass. Deeper boreholes intersect smaller voids with overall low hydraulic conductivity.
(After LeGrand, Davis, De Wiest, modified)

Fig. 11A - Il grafico mostra la generale diminuzione di portata dei pozzi a seguito della ridotta conducibilità idraulica che si riscontra per profondità crescenti. Pozzi più profondi intersecano vuoti più piccoli, con una conducibilità idraulica generale minore.

Fig. 11A - General decrease of water well yields due to the reducing hydraulic conductivity with depth in fractured rocks.

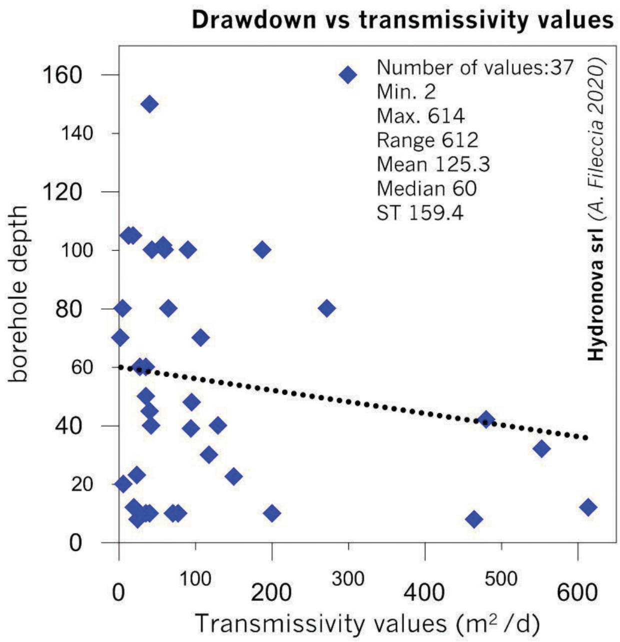


Fig. 11B - Diminuzione progressive della trasmissività con la profondità in un acquifero multistrato (Groundwater numerical model of Sofia Plain, HydroNova srl 2020)

Fig. 11B - General decrease of aquifer transmissivity with depth in a multilayered aquifer system (Groundwater numerical model of Sofia Plain, HydroNova srl, 2020)

legal disputes. In fact the final execution is the landowner's responsibility. Instead the decision to drill for a water well should start with an independent hydrogeologist who carries out a feasibility study to highlight the likelihood of success, and who then engages a third-party drilling contractor and provides the necessary guidance. In many situations the volumes requested by the client cannot be guaranteed and the low well discharge that results may be due to poor working practices as well as the aquifer's low transmissivity. For the latter case few actions can be taken to remedy, hence a hydrogeological field survey at a preliminary stage is highly advised. Last but not least, the engineer's duties include, for instance, managing issues related to the water delivery or specific drilling tools, the disposal of mud waste, and in particular all concerns related to the pump efficiency, head and electricity cost for water delivering on the net. First-time client requests are frequently overly, general and fall short of the actual aquifer potential. The plausible explanation rests on the fact that many prospective customers lack geological expertise. The hydrogeologist should serve as a point-of-contact at this point, making an effort to understand the client's actual demands and confirming the hydrogeological situation.

He will then prepare a conceptual model of the area and advise the driller on a set of drilling specifications based on the lithology and estimated aquifer type. These specifications will serve as a general guidance for the tender and possibly adopted to the conditions encountered during work. The hydrogeologist's ultimate objective is to design an abstraction point that is compatible with the resource at hand, does not result in adverse impacts and can function effectively for a long enough period of time. It is crucial that the client is fully informed of the advantages and disadvantages of each strategy.

Which are the specific tasks of the hydrogeologist?

In short hydrogeologist should ensure the following (Brassington, 2007; Misstear, Banks, Clark 2006; Australian Drilling Industry Training Committee, 1997; Sterrett, 2007):

- Perform a preliminary hydrogeological investigation and checking with client's requirements
- Liaise with the drilling contractor and assess the drilling specifications
- Conduct the geological analysis during drilling, development and completion
- Schedule, assist and interpret the aquifer tests
- Assess the data interpretation and report
- Prepare all the requested documentation for compliance with reporting requirements and in order to obtain the necessary abstraction permits

After completing the appropriate research on existing studies and reports for the area of work and one or more site visits, the consultant is expected to prepare a general note that will assist in scheduling the drilling works and specifications for the contractor, such as:

1. Objective of the work
2. Estimated lithology and type of aquifer
3. Piezometric surface and water point survey
4. Pollution centers in the proximities
5. Influence radius due to other pumping wells
6. Hydrogeological conceptual model (to be refined during the study)
7. Preliminary evaluations on hydrogeological parameters
8. Preliminary evaluations on type and length casing and screens, available discharge, pump power, well depth, diameter, drilling type etc.
9. Preliminary well design, type of tests to perform
10. Meetings with the drilling contractor and the client

The following is an example of the key data that must be collected before and during the study for the siting and completion of a water well: (more details on the free resources at the end of this paper and the book of Misstear, 2006).

Preliminary investigations:

This stage is necessary to pinpoint regional problems and gather data from earlier research, geological and hydrogeological maps and local problems. The map should depict a region of a few square kilometers around the drilling location that is large enough to accurately identify the aquifer to exploit.

The hydrogeological map at 1:10000 scale, should illustrate the following main features:

- Different hydrogeological formations
- Temporary and perennial streams with estimation of their discharges
- Springs and their main regime
- Known water wells with description
- Water table elevations (ideally assessed during recession and wet periods)
- Hydrogeological profiles defining type of aquifer, thickness, lithology, piezometric level

The job is accompanied with field visits and desk work for the listing of:

- all the potential pollution centers
- the main hydraulic properties of the aquifer (T, S) and their source
- a collection of aquifer water quality data
- an approximate evaluation on aquifer discharge and radius of influence based on the planned extraction volumes (this will help in considering the well size and pump power)

Drilling a pilot hole (piezometer) about 10 to 30 meters away from the anticipated location of the final water well is recommended when extractions are significant compared to the transmissivity of the aquifer. The piezometer will be used to determine the lithology, plan the well design, monitor the piezometric level during the aquifer test and compute the storage coefficient. In order to determine the maximum permissible discharge that the aquifer can support safely for an extended length of time, it will be critical to estimate the future piezometric levels at various distances and timeframes based on the proposed abstraction volumes.

Drilling assistance (casing and development)

Some points to account for during the geological assistance:

1. Survey of the drilling site and location of any facilities
2. Selection of the drilling diameter in relation to the abstraction rate
3. Selection of drilling, sampling methods and fluid (water, air, mud)
4. Selection of pipes, screens, casing material and diameters
5. Computing the gravel pack volumes and size
6. Hole depth supervision
7. Selection of the type of borehole log
8. Specific actions (cementation, well development, pump type etc.)
9. Pump installation for aquifer tests and dip pipe for multi-parameter sensor (it is advised to start monitoring the aquifer 2-3 days before the test to identify existing natural or artificial stresses)
10. Planning of the aquifer and well efficiency tests (piezometer recommended), such as:
    - Specific capacity (SC)
    - Step drawdown test (SDT) recommended 4 steps, 2 hrs each with final recovery
    - Constant rate test (CRT) with recovery, recommended at least 6-12 hrs duration
    - Data processing water well efficiency, hydrogeological parameters (K, T, S, R)
11. Water sampling during test
12. Specifications for corrosive water
13. Specification to increase the general aquifer permeability
14. Specifications for special works around the well head (operating cabin, geotechnical situation)
15. Video-inspection after well completion
16. Installation of the monitoring equipment and data transfer type (telemetry, etc.)
17. Specifications for sludge treatment and water conveyance
18. Specifications for the well operation during time
19. Miscellaneous measures (geo-referencing, information sheet and database updating…)
20. Data processing and final report with sustainable yield evaluation and maintenance operations

Well performance and aquifer tests

After completion of a water well and its full development, the next step is performing a pumping test.

A pumping test, often called a well test, is a method of determining how easily groundwater flows into a well. It involves pumping at specified rates while assessing the impact on water levels (drawdown and recovery) preferably in one or more observation boreholes (piezometers) as well as in the pumping well. The results of the pumping and the aquifer

DOI 10.7343/as-2023-656

tests which offer information on aquifer properties and well performance, typically predict the short term yield. The long-term viability of the supply must always be taken into account when planning a well or well field. One example of additional measurements is the change in water chemistry or physical composition of the water being pumped during the test.
A pumping test is probably the most accurate method that can be used to estimate aquifer parameters such as: hydraulic conductivity, transmissivity and storage coefficient. Nevertheless, pumping tests can be time consuming and often costly. It is important, therefore, to plan and carry them out with care to obtain the best quality information for the effort involved. Because of the complexity of the groundwater flow systems and the complicated geological circumstances, the data obtained from pumping tests may not always be simple to understand. Gathering the data required to understand the aquifer mechanics is a crucial factor to take into account when planning a well test; in other words the test itself must stress the geological formation by withdrawing large amounts of water over an extended period of time and creating a cone of depression (Kasenow, 2001; Kruseman, de Ridder, Verweij, 2000).
When water is pumped out from a well, an area of low pressure is created in the casing/screen column and water rushes from high pressure outside into low pressure inside. Drawdown occurs from either gravity drainage in a water table aquifer or when hydraulic pressure drops in a confined aquifer. The measured drawdown is greatest at the production well and decreases as it gets away from the well. This hydraulic gradient expands as ground water continues to move from high to low pressure areas replacing water that is being discharged. This expansion process diminishes at a zone of balance when recharge from the external groundwater matches the well discharge. The physical shape that results is known as a cone of depression (Figure 12).

The expansion of the cone slows with time because more and more volumes of groundwater is being used to replace what is abstracted. The rate and extent of the cone's expansion depends on:

- Pumping rate
- Time of pumping
- Transmissivity, hydraulic conductivity, storage coefficient of the aquifer
- Location of recharge areas and boundaries

Pumping tests can be divided into various types of increasing complexity and cost:

1. Specific capacity test.

Specific capacity tests are used to establish the average yield of a new well or check the performance of an existing one. It normally takes a few hours, or usually less. The well is pumped at a rate slightly more than its normal daily value and the corresponding drawdown is recorded. The specific capacity is the ratio of the discharge (Q) to the corresponding maximum drawdown (s) at the end of the pumping:

Specific capacity: Q/s

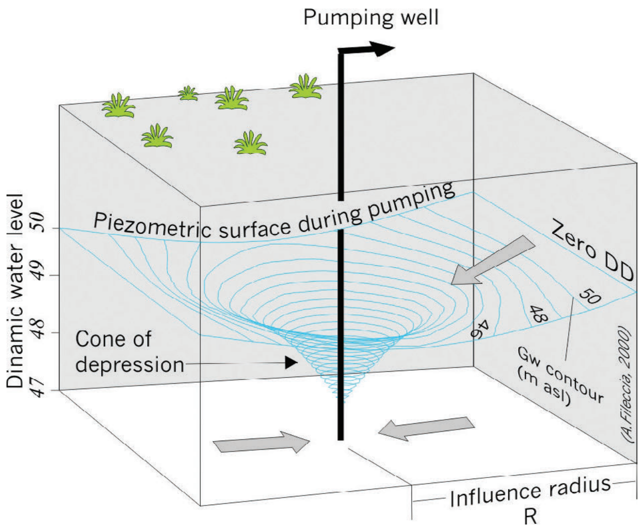


Fig. 12 - Cono di depressione in un acquifero ideale durante il pompaggio a portata costante. L'abbassamento nel pozzo diminuisce lentamente nel tempo e si espande lateralmente nell'acquifero. Alla fine si produce un gradiente idraulico che si annulla dove la ricarica eguaglia la portata estratta. La forma che idealmente si ottiene è chiamata cono di depressione e la distanza alla quale l'abbassamento è trascurabile costituisce il raggio d'influenza.

Fig. 12 - A cone of depression produced in an ideal aquifer during pumping at a constant rate. The drawdown in the well decreases slowly with time and expands laterally in the aquifer. Eventually a hydraulic gradient occurs, until is reached a point, where ground water recharge is equal to the water being discharged. The expanding gradient is called the cone of depression and the distance at which a nearly zero drawdown is reached is called influence radius.

2. Step drawdown test (SDT)

Normally completed in 6 – 8 hours, the Step Drawdown Test involves pumping at increasing rates for three or better four equal periods of 1-2 hours each. The relationship between pumping rate and drawdown is used to define the hydraulic characteristics of the well, allowing the most efficient pump to be selected. The test also includes monitoring the recovery of water levels, after the pump has been shut off, therefore allowing for a better estimate of the transmissivity.

3. Pumping or well test

Pumping (well) tests are used to obtain a better estimate of certain hydrogeological parameters. The borehole is pumped at a constant rate for several hours (24 or longer) followed by a recovery test.

4. Aquifer tests.

Aquifer tests entail a constant rate test, with a discharge value selected from a preceding specific capacity or SDT test, followed by recovery and designed to provide information on aquifer's hydraulic properties. Aquifer tests also involve measurements in a few observation wells over a period of one to several days (commonly referred to as multiple well tests). The piezometers or observation wells, must have a particular design in order to give a better response during the test.

A good description of these particular tests can be found in the instruction manual of SATEM (Software for aquifer tests evaluation) (SATEM, Selected Aquifer Test Evaluation Methods : a microcomputer program / J. Boonstra).

Main conclusions

Prioritizing the success of a new water well is often a tradeoff between competing factors, including the available budget, the client's requirements, the competence of the drilling contractor, the stresses on the environment and the available aquifer resources in the area. When the new borehole becomes operational unanticipated repercussions can result from uninformed well siting and design such as unproductive or clogged boreholes, aquifer mixing, underground flow diversion, soil subsidence, drying up of springs etc.

These concerns are difficult to consider and manage from an environmental point of view. To mitigate against such undesirable environmental consequences a proper hydrogeological approach must always be included in every drilling project. Groundwater investigations for siting and designing water wells must adhere to the widely accepted protocol that includes five distinct but crucial steps: (1) assessment of the local hydrogeological model, (2) preliminary well design, (3) drilling assistance, (4) aquifer tests and (5) a final well design with recommendations for routine well maintenance. The approach which has been described in numerous reports, significantly aids in the accurate planning groundwater development in the short- and middle-term, while also ensuring the aquifer's sustainability.

Acknowledgment: I thank the colleagues eng. Paolo Mastrocola and Casey Walther for their useful suggestions and review and the company HydroNova (HYPERLINK "http://www.hydronova.tech" www.hydronova.tech) for providing some of the raw data used in the text.

REFERENCES

Alley, W,M., Reilly, T,E. & Franke, O,L. (1999). Sustainability of ground-water resources, U.S. Geological Survey Circular 1186, 79 p.

Australian Drilling Industry Training Committee. (1997). Drilling: the manual of methods, applications, and management. CRC Press.

Banks, D., Morland., G., Frengstad, B. (2005). Use of non-parametric statistics as a tool for the hydraulic and hydrogeochemical characterization of hard rock aquifers. Scottish journal of Geology 41(1): 69-79

Brassington, R., (2007). Field Hydrogeology. Open Univ. Press J. Wiley and Sons

Driscoll, F,G, (1986). Groundwater and wells, Johnson Division.

Fileccia, A. (2015). Some simple procedures for the calculation of the influence radius and well head protection areas (theoretical approach and a field case for a water table aquifer in an alluvial plain) Italian Journal of Groundwater n. 141, https://doi.org/ 10.7343/AS-117-15-0144

Franke, O.,L., Reilly, T,E., Pollock, D,W., & LaBaugh, J,W. (1998). Estimating areas contributing recharge to wells – Lessons from previous studies, U.S. Geological Survey Circular 1174, 14 p.

Freeze, R.A, & Cherry, J,A. (1979). Groundwater, Prentice Hall, Englewood Cliffs, New Jersey,

Heath, R,C. (1983). Basic ground-water hydrology, U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Kasenow, M. (2001). Applied Ground-Water Hydrology and Well Hydraulics 2nd Ed. 15

Kresic, N., & Mikszewski, A. (2013). Hydrogeological conceptual site models Data Analysis and Visualization, CRC Press

Kresic, N. (2007). Hydrogeology and groundwater modeling, CRC Press

Kruseman, G.,P., de Ridder, N,A., Verweij, J,M. (2009). Analysis and evaluation of pumping test data. ILRI n. 47.

Maurice, L., Taylor, R,G., Tindimugaya, C. et al. (2019). Characteristics of high-intensity groundwater abstractions from weathered crystalline bedrock aquifers in East Africa. Hydrogeol J 27, 459–474 https://doi.org/10.1007/s10040-018-1836-9

Misstear, B. (2012). Some key issues in the design of water wells in unconsolidated and fractured rock aquifers, Italian Journal of Groundwater n.129, https://doi.org/10.7343/AS-006-12-0013

Misstear B., Banks D., Clark L. (2006). Water wells and boreholes. John Wiley and Sons, LTD

Sterrett, R,J,. 0978779304, 9780978779306. (2007). Groundwater and Wells. 812 p. Johnson Screens

Online resources:

https://www.groundwater.org/get-informed/basics/glossary.html (The Groundwater Foundation)

https://www.epa.gov/ceam/wellhead-analytic-element-model-whaem-release-notes (Software WHAEM from EPA)

http://www.filecciageologia.it/Download/Lezioni_idrogeologia/GW_drilling_full_course_Fileccia_20221220.rar (slides from a training course on groundwater researches and water well drilling)

SATEM, Selected Aquifer Test Evaluation Methods : a microcomputer program / J. Boonstra Wageningen, https://edepot.wur.nl/82326 The Netherlands: International Institute for Land Reclamation and Improvement, 1989