Cause and prevention of clogging of wells abstracting groundwater from unconsolidated aquifers

van Beek, C.G.E.M.

2010

Summary

Groundwater serves many purposes: as raw material for the public and private drinking water supply, for the production of beer and beverages, and in agriculture for irrigation and watering cattle. Groundwater abstraction serves for stabilizing structures in civil engineering, like dams and tunnels, for keeping dry building excavations, and for reclamation of polluted groundwater. At the moment, groundwater is also increasingly used for energy storage (Aquifer Thermal Energy Storage, ATES).

Groundwater is usually abstracted with the help of wells. At present there are probably millions of drilled wells, either permanently or temporarily. In unconsolidated sediments these drilled wells consist of a well screen with on top a well casing. The annular space between the well screen and the well bore is filled up with gravel, the so-called gravel pack. In order to prevent short-circuit groundwater flow, the gravel pack is sealed on top with clay. For the same reason pierced clay deposits are also restored with clay. After construction, the well has to be developed in order to remove the drilling mud, which is plastered on the well bore and invaded a short distance into the aquifer. But remarkably, the criterion for a developed well consists of the absence of sand in the abstracted groundwater at a discharge rate usually twice the design capacity, and not of a successful removal of drilling mud.

After some time, drilled wells may become clogged. Clogging is characterized by a decrease in the specific capacity: the discharge rate (m^3/h) divided by the drawdown (m), where the drawdown equals the difference in water level in the well during operation and rest. In well clogging, two causes may be distinguished: clogging of the slots of the screen (screen slot or chemical clogging) and clogging of the well bore (well bore or mechanical clogging). Both types are easy to distinguish, as screen slot clogging is characterized by an increasing difference in water level during abstraction inside and outside the well, and well bore clogging by the absence of an increase of this difference.

Screen slot clogging

Screen slot clogging is caused by an accumulation of chemical precipitates, whether or not accompanied by biomass, in the screen slots. Most frequently, these precipitates consist of iron(III) hydroxides. These iron(III) hydroxide precipitates are not confined to the screen slots, but are also present upstream in the gravel pack, and downstream on the well casing and submersible pump and in the field lines. Precipitates will develop if the well abstracts two incompatible water qualities: in the case of iron(III) hydroxide precipitates shallow groundwater containing oxygen and deeper groundwater containing iron. In iron(III) hydroxide precipitation three oxidation processes may be active: homogeneous, heterogeneous and biological oxidation. In homogeneous oxidation, iron(II) and oxygen are mixed together and iron(III) hydroxides will precipitate. This process is slow under neutral conditions, and the rate increases with increasing pH and increasing iron(II) and oxygen concentration. As soon as some iron(III) hydroxide precipitates are present, heterogeneous oxidation will occur, characterized by adsorption of dissolved iron(II) by these precipitates and subsequent oxidation and hydrolysis of adsorbed iron(II). In this two stage process, the adsorption process is actually rate limiting. Under neutral conditions adsorption is fast, and the rate increases with increasing pH, iron(II) concentration and iron(III) hydroxide concentration, or better with increasing iron(III) hydroxide surface area. Everywhere where conditions are at least acceptable, bacteria adapted to those conditions will be present. Consequently, aquifers containing both oxygen and iron(II) will contain Iron Oxidizing Bacteria (IOB), which sooner or later will be attracted by the discharging well. As soon as IOB are present, biological oxidation will occur, characterized by adsorption of dissolved iron(II) on their cell walls and on their Extracellular Polymeric Substance (EPS) and subsequent oxidation and hydrolysis of adsorbed iron(II). The physiological optimum conditions for IOB are characterized by slightly acid to neutral conditions and a low oxygen concentration. If both iron(III) hydroxide precipitates and IOB are present, there is a fierce competition between heterogeneous and biological adsorption of dissolved iron(II). In this reasoning the adsorption rate of dissolved iron(II) by on the one side iron(III) hydroxide surfaces and on the other side biological surfaces is critical, and not so much the oxidation rate of adsorbed iron(II).

Initially, in a new well, only homogeneous iron(II) oxidation will occur, and this is a slow process. Possible developed precipitates will be carried away with the abstracted groundwater. This situation changes radically during periods of rest: during these periods there is ample time for reaction, and moreover, flocs, if accumulated on the screen of the submersible pump, may twirl down, even deep down in the well. In addition, in the process of filling in the cone of depression around the well, water may flow out the well through the slots into the gravel pack. If present, iron(III) hydroxide flocs may then precipitate and accumulate in the slots and gravel pack. As soon as abstraction starts again, the iron(III) hydroxide precipitation process is accelerated by the occurrence of heterogeneous oxidation. IOB have excellent adhering properties. As soon as they have reached the well, they will stick there, in particular during periods of rest.

In this reasoning, screen slot clogging may be prevented by positioning the well screen over a depth interval with a homogeneous chemical composition. If this is

not possible, clogging may be retarded by continuous abstraction, whether or not with the help of a variable discharge pump, by taking advantage of the slow reaction kinetics. As a result of these slow reaction kinetics, precipitates will not precipitate in the screen slots, but in the submersible pump and field lines. This recommendation not only applies to the development of iron(III) hydroxide precipitates, but to all precipitates with slow reaction kinetics.

Continuous abstraction as a preventive measure was already known by experience, but this reasoning gives some background for this phenomenon.

Well bore clogging

In well bore clogging, particles have been suspect for a long time, but it was not possible to ascertain their presence, let alone their role. Moreover, as the aquifer may be considered as a giant filter, their presence was not taken for granted. Once there was an opportunity to count particles in abstracted groundwater with a commercially available particle counter, their presence could be clearly demonstrated.

In these particle counters a laser beam is directed through a flow through cell, and the number of shadows, together with their size, is counted on the opposite side with the help of a sensor. In this way the particle concentration together with the corresponding particle size distribution, is obtained, here with a minimum diameter of 2 μm. Obviously, shadows are projected by all opaque materials, whether it be minerals, organic matter, bacteria or iron(III) hydroxide precipitates, but also by gas bubbles. In order to be sure that all counted particles originated from the aquifer, in this study particle countings have been limited to clean wells. Abstracted groundwater from these wells contains no oxygen, and the low sulfate concentration indicates the occurrence of, past or active, sulfate reduction.

Particle countings were executed on abstracted groundwater under normal operation conditions, obtained via the sample valve on the well head. Particle concentrations always showed a peak after switching on the well, which decreased quickly to more or less stationary values. These stationary concentrations range between 2 and 120 particles/ml, with 1 to 3% of the particles >15 μm. Particle concentration and particle size distribution were dependent on the abstraction rate: the higher the rate, the higher the concentration and the coarser the particles. Particle size distributions in water are usually described with the help of the Pareto distribution. However, compared to the Pareto distribution, in abstracted groundwater particles >7 μm were underrepresented.

Particle concentrations in abstracted groundwater are much lower than concentrations measured in groundwater obtained from monitor wells. Apparently, the particle supply around abstraction wells becomes exhausted. This exhaustion may be explained by the recurrent mobilization of particles each time the pump is started, of which the intensity decreases with increasing distance to the well. Filtration theory shows that under average groundwater flow conditions, mineral particles with an average diameter of circa 0.5 μm are most mobile. Smaller particles are less mobile due to diffusion, and larger particles due to sedimentation. This limited mobility of larger particles may also explain the under representation of particles >7 μm in abstracted groundwater.

Peak concentrations amounted to several thousand particles/ml and these concentrations appeared to originate from the well bore. Apparently, particles accumulated on the well bore during the preceding abstraction period, and are mobilized by the acceleration exerted by the water set in motion after the pump is switched on again. This behaviour was demonstrated by all wells, clogging and non clogging. Comparison of well operation mode and drawdown data learned that long continuous abstractions resulted in an increase in drawdown, which indicates the occurrence of well bore clogging. Apparently, a starting pump is able to mobilize a certain number of particles. If, on average, during preceding abstraction periods more particles are accumulated then switching on the submersible pump is able to mobilize, the well will start to clog. And, on the contrary, if on average less particles are accumulated than a starting pump is able to mobilize, there will be no well bore clogging. Consequently, well bore clogging may be prevented by intermittent abstraction. This prevention method was confirmed by results of field measurements.

Remarkably, abstracted groundwater from all wells contains particles, but not all wells clog. Possibly, well operation of these wells is such that clogging does not occur. It is also possible that the abstracted groundwater contains less particles and/ or the well bore is less susceptible to accumulation of particles, for instance as a result of a more complete well development, a larger well diameter or a coarser aquifer.

Thus, prevention methods for both types of well clogging are just the opposite: continuous operation for wells susceptible to screen slot clogging, and intermittent operation for wells susceptible to well bore clogging.

Particle mineralogy

Information on morphology and chemical composition of particles was obtained with the help of automated Scanning Electron Microscope – Energy Dispersive X-ray Spectroscopy (SEM-EDS). Particles were identified as minerals by comparing the measured chemical composition with the average chemical composition of minerals from handbooks. The greater part of the particles consisted of quartz and calcite with feldspars, glimmers and clay minerals and a small contribution of pyrite. Iron sulphide particles were clearly smaller than other particles. No iron hydroxide particles were present. Apparently, the particle mineral composition is governed by the mineral composition of the aquifer, as source of particles, and by the groundwater chemical composition, as controlling the chemical stability. It was not possible to identify in a direct way organic matter particles, but there were only a few particles containing no cation and/or silicon.

Compared to the mineral composition of the aquifer grains, calcite was overrepresented in particle composition. As the particle size distribution and the morphology of the calcite particles were not different from those of the quartz particles, this overrepresentation cannot be explained by morphological differences. This difference can also not be explained by dissolution of calcite aquifer grains or calcite coatings as groundwater was saturated or over saturated with respect to calcite. Oversaturation may lead to precipitates, but calcite particles were larger than those of pyrite, which are definitely generated by oversaturation. Moreover, not all ground waters were oversaturated with respect to calcite. This leaves crushing of calcite grains under the weight of the overlying soil layers, and by the vibrations exerted by starting pumps, as the most likely cause. This also explains the overrepresentation with respect to quartz: quartz is much harder than calcite and consequently much harder to crush.

Most surprising was the presence, up to 25%, of particles consisting of sulfides of copper, lead and zinc, and particles consisting of iron whether or not containing chromium and nickel and of aluminum. These particles are considered as corrosion products from the well and from the sample valve on the well head, and as abrasion products from the submersible pump.

Well incrustation and well design criteria

At last, well design criteria in relation to incrustation were evaluated. These criteria are not correct and internally conflicting: in order to prevent incrustation of wells they aim to prevent turbulent flow. But aside from better mixing, turbulent flow has nothing to do with chemical processes: as long as no solubility products are exceeded and fast reaction kinetics are involved, no precipitates will develop. On the other side these criteria permit higher flow velocities in coarser aquifers. But the coarser the aquifer, the lower the flow velocity where laminar flow changes into turbulent flow.

Probably higher design velocities may be applied, allowing at least incipient turbulent flow. For the construction of new wells, it is advised to make more use of experiences from existing wells or from related well fields.