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Cover photo:
© I. Stober, Thermal water spring, showing sinter of iron-rich calcite. Participant of the EAGE/EFG photo contest 2015.

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Equalising flow in water wells: from theory to practical results

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Well ageing processes (loss of yield, sand pumping, turbidity, mineralogical incrustation and biofouling) area related to a non-uniform, high flow regime in the well. In that paper we review flow equalisation, a technique which counteracts non-uniform flow pattern, and present results from two experiences with Spanish water wells. In this study previously published results for equalisation were reproduced and equalization's applicability was extended to highly incrusted wells. In a time when economic and environmental aspects lead to increasing interest in rehabilitation techniques, equalisation deserves attention for its results in the improvement of well hydrodynamics and reduction of well ageing processes.

*Des signes de vieillissement de puits (perte de débit, sable dans pompage, turbidité, incrustation minérale et accumulation de micro-organismes), sont liés à un régime de puits non uniforme et de débit de crue. Dans cet article, nous examinons le contrôle de débit (*équalisation*), une technique qui régule le modèle de débit non uniforme, et présentons les résultats fournis par deux expériences réalisées sur des puits, en Espagne. Lors de cette étude, des résultats publiés précédemment pour l'*équalisation *ont été reproduits et les conditions d'applicabilité de ce contrôle de débit ont été étendues à hauteur de puits fortement incrustés. Au moment où les critères économiques et environnementaux contribuent à un regain d'intérêt pour les techniques de réhabilitation, l'*équalisation *mérite une attention particulière pour ses résultats dans l'amélioration des caractéristiques hydrodynamiques et la réduction des phénomènes de vieillissement des puits.*

Los procesos que deterioran los pozos (pérdida de rendimiento, arrastres, turbidez, incrustación y biofouling) están estrechamente relacionados con la existencia de un régimen de flujo heterogéneo con velocidades elevadas. En éste artículo se presenta una revisión de la ecualización del flujo, una técnica que corrige el régimen de flujo, y se presentan los resultados de dos experiencias en pozos en España. En ellas se han reproducido resultados publicados y se extiende la aplicabilidad de la ecualización a pozos fuertemente incrustados. En una época en la que la rehabilitación de pozos gana aceptación por criterios económicos y ambientales, la ecualización es una técnica de interés por sus resultados, al mejorar el régimen de flujo y reducir los procesos que causan el envejecimiento de los pozos.

1. Introduction

The utilisation of fresh water, especially groundwater, has been increasing all over the world. This is why the maintenance of wells and development of new techniques for sustainable operation and well diagnostics are very important. Well ageing processes are related to the flow regime. The aim of this paper is to focus on the importance of flow regime in the well ageing process and to show practical results using a technique that improves flow regime and reduces well ageing.

1.1. The basics of well hydraulics

The general approach to well hydraulics (Driscoll, 1986) assumes that the flow enters the well uniformly distributed along the screen. Flow entrance velocity is simply estimated as the ratio between discharge and the open area of the screen without any consideration of other variables. Traditional well design considers low entrance velocity a key factor in order to maintain laminar flow, reduce head losses, allow better well development and reduce ageing (Sterrett, 2007; Wenling *et al.*, 1997).

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But well hydraulics are actually more complex, as has been outlined by theoretical analyses and laboratory simulation since the 1960s. Pump suction creates a lower pressure area that modifies the original schema of a uniform vertical flow distribution (***Figure 1***). Assuming a pump located above the screen area, the flow is characterised by:

- a maximum inflow velocity zone in the upper area of the screen, located close to the pump and decreasing exponentially downwards (Kirschmer and Ueker 1966, Kirschmer 1977).
- a vertical flow component in the gravel pack created by the unequal flow distribution along the screen (Truelsen, 1958). These vertical flows could increase the inflow velocity by up to 50 times (Ehrhardt, 1986).

As a result of this flow distribution, water flows mainly across the uppermost part of the screen, whereas water from the lowest part of the well flows through the gravel pack, also rising to the upper part of the screen, so that the rest of the screen acts weakly or does not act at all (Pelzer, 1991).

1.2. Flow pattern and well ageing processes

The presence of areas of high velocity creates zones prone to several processes that cause the ageing of wells and also affect the water quality: sand pumping and increased turbidity, mineral incrustation and biofouling.

For these flow patterns, it is very common for the upper part of the screen to display more development of incrustations. When the pump is located at the

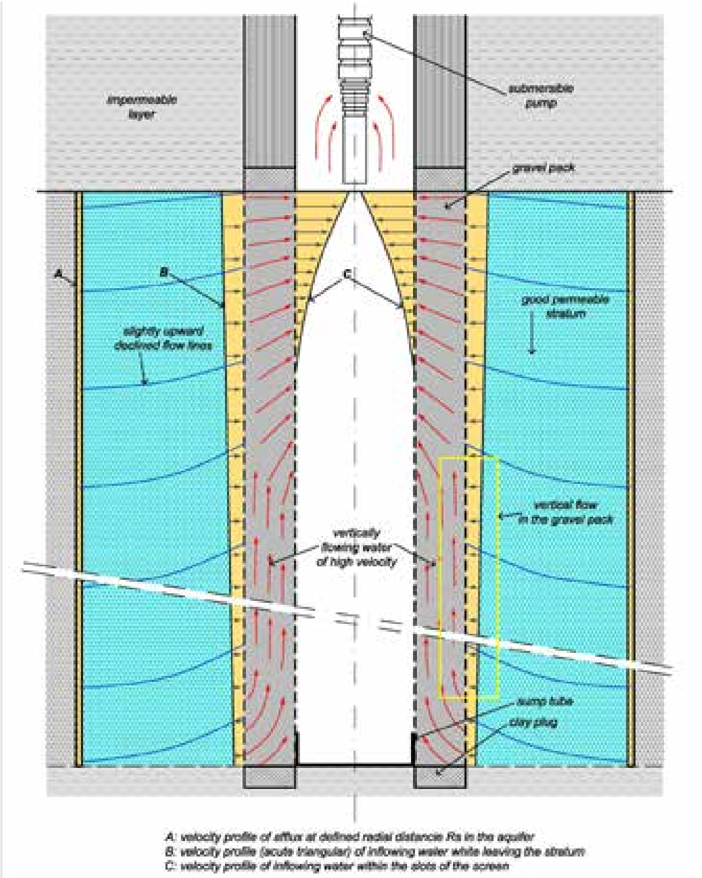

Figure 1: Flow distribution inside a well: flow concentrates in the area closest to the pump; this unequal distribution along the screen creates a vertical flow through the gravel pack located in the annular space (modified from Pelzer, 1991).

bottom, incrustations develop from the pump upwards. Caliper measurement and camera inspection allow quantification of the thickness of incrustation, which helps to describe the flow pattern inside the well (***Figures 2 and 3***). In the first example (***Figure 2 and 3, left***), the process of incrustation has led to complete clogging from the pump area to the bottom. The well bottom is filled with sediments due to the failure of the bottom concrete pad because of suffusion. In the second example (***Figure 2 and 3, right***), the caliper measurement shows a first area (***arrow in Figure 2, right***) of thick incrustations at 50 m depth, related to the initial position of the pump, while a main incrusted area is near the second pump position. .

Houben and Treskatis (2007) describe a gradual pattern of incrustation that starts in the area of high velocity (usually the area closest to the pump) and, as incrustation closes the openings, the area of maximum flow displaces downwards to less incrusted areas, until the screen is completely incrusted.

1.3. Equalisation and SFCD

Equalisation is a technique which tries to counteract the asymmetrical flow pattern in the well described above, creating a uniform distribution of flow over the total length of the well screen. The first ideas for equalisa-

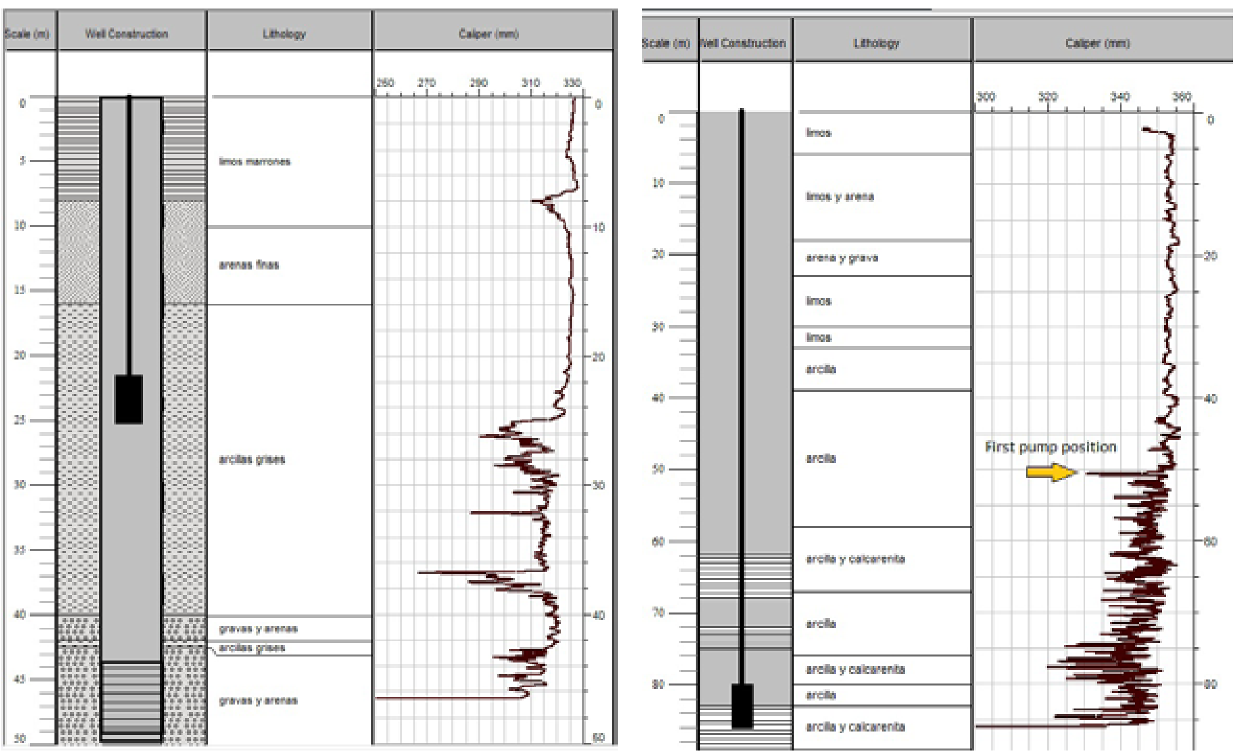

Figure 2: Well profile and caliper measurement of wells with a different pump position. The left-hand example is comparable to Well B and the right-hand profile corresponds to Well A, as shown below.

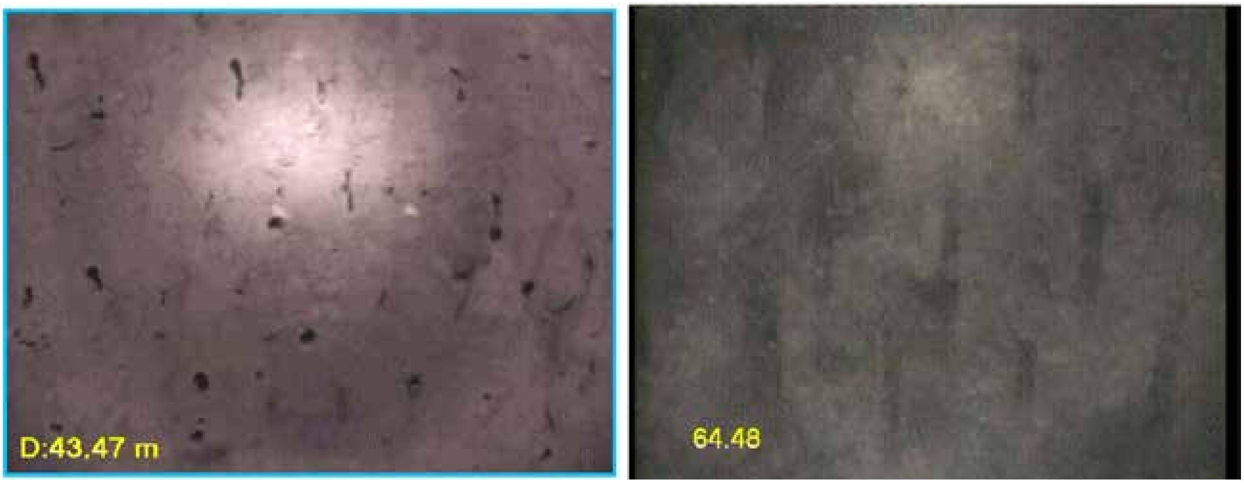

Figure 3: Images of a highly incrusted screen in a well comparable to Well B (left) and of the highly incrusted screen of the above-mentioned Well A (right). Source: Construcciones Iniesta.

Figure 4: Installation of a suction flow control device (SFCD) in a water well.

tion came from Truelsen (1958), and were later developed by Pelzer and others.

Equalisation is performed by a Suction Flow Control Device (SFCD) (called Sistema Ecualizador del Flujo (SEF) in Spain). An SFCD is an engineered slotted pipe inserted inside the well casing that carries all the water pumped. Slot distribution tends to equalise the velocity of the water across the screen, thus tending to a more laminar and less turbulent flow and reducing the vertical flow component in the annular space.

The original device (late 1970s-80s) consists of two concentric thick-walled pipes closed at the bottom, with uniform slotted jackets and an infilling of plastic granulate in the annulus. It was designed on the principle of increasing high flow resistance to counteract the natural flow areas. The device was easily affected by incrustation (Ehrhardt and Pelzer, 1992) and abandoned in Europe, though a comparable design with a resin-bound gravel pack is still used in the USA. An improved design (late 1980s onwards) consists of only one thin-walled pipe closed at the bottom with perforations that increase from the upper part to the bottom. The device can hang on the rising mains with the well pump inside or rest on the bottom of the well. The latter is the current standard (***Figure 4***).

Although SFCDs were designed several decades ago, their use in Europe has been very limited, probably due to the limited results of the first designs and the need for a specific design for each well, calling for a diagnosis of the well. For these reasons experience with those devices is very limited, despite the sound hydraulic criteria on which they are based.

2. Experiences and results

In this paper we present the first results of the installation of SFCD devices in Spain. The work has consisted of the preliminary diagnosis of the water well, the installation of SFCDs and the monitoring of the equalised well in order to evaluate well performance.

2.1. Well Diagnosis

Well A, in the Valencia area, is a 25-year-old well, 90 m deep and 350 mm in diameter, drilled by percussion with 18 m of screen in the lower part (***Figures 2 and 3***). The well is constructed in a confined granular aquifer.

Well A was diagnosed by geophysical testing and a pumping test. The well was highly incrusted with 2-3 cm of hardened iron-manganese incrustations. The last 4 m were full of gravel from the gravel pack, indicating the bottom concrete pad had been broken by suffusion phenomena. An SFCD was installed with no rehabilitation, simply using an air-lift to remove sediment from the bottom. A 3-year record of monitoring is available.

Well B, in the Barcelona area, is a 51-year-old well, 50 m deep and 600 mm in diameter, drilled by percussion with a 6 m screen

Figure 5. Well A, heavily incrusted rising main (left). Accumulation of fresh Iron precipitates on the rising main after a 12-hour pumping test (right).

in the bottom. The well has been rehabilitated several times and in 1994 was partially recased with 500 mm steel casing from the top to above the screen area.

Well B has been diagnosed with a pumping test only, but data from other wells in the same area show heavy incrustation of the screen with 1-2 cm of hardened iron-manganese incrustation (***Figures 2 and 3***). An SFCD device was installed without any previous rehabilitation. From monitoring we have a 6-month record of post-installation performance.

2.2 Results

2.2.1. Observed changes in well losses

The introduction of an SFCD is physically equivalent to the installation of a second casing inside a well (recasing). Recasing tends to create additional friction, which causes extra head loss and consequently a decrease in specific discharge or yield (ratio discharge/drawdown). In our experience the recasing of a well with a screened commercial PVC pipe could cause a reduction in specific discharge of around 20%.

Although it might seem counter-intuitive, the SFCD does not cause head losses (Pelzer, 1991; Wathelet, 1994) because the effect of equalisation reduces dynamic head losses (turbulence and the vertical flow component) and this counteracts the head losses created by the friction of the new pipe.

In Well A, immediately after the installation of SFCD, there was a first period of three months (from Q2 2012 to Q3 2012) where a sharp loss of yield occurred (-45 % in the first weeks, -20% on average). In a second period (from Q4 2012 to Q4 2013), yield increased with a gain of up to +30% on the original yield. In a third period (from Q1 2014 to present) yield decreased to the values prior to installation. The same loss in yield was also observed in the control well, where loss in yield of about -5% was observed (***Figure 6***).

Well B had lost -30% of its yield in the last 30 years. After installation no change in yield was observed. Two months later a +10% increase was observed (***Figure 7***). Because of the recent installation data (beginning in 2015), few results are available for the evolution of well performance due to this device.

2.2.2 Observed changes in incrustations

None of these units has been video inspected since installation so we do not

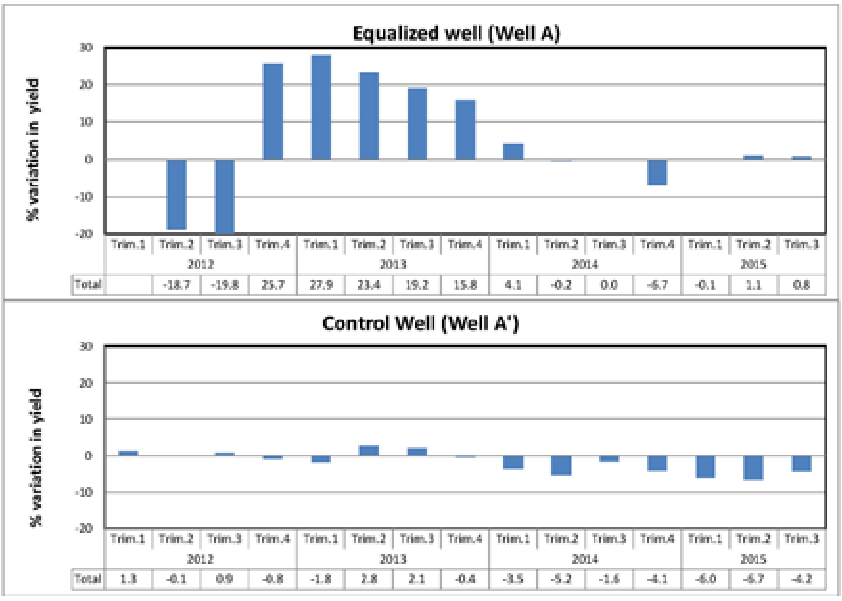

Figure 6: Evolution of yield in two old incrusted wells in a well field in the Valencia area. Well A was equalised with an SFCD in June 2012. Well A' is the control well. Values correspond to a quarterly average based on daily values.

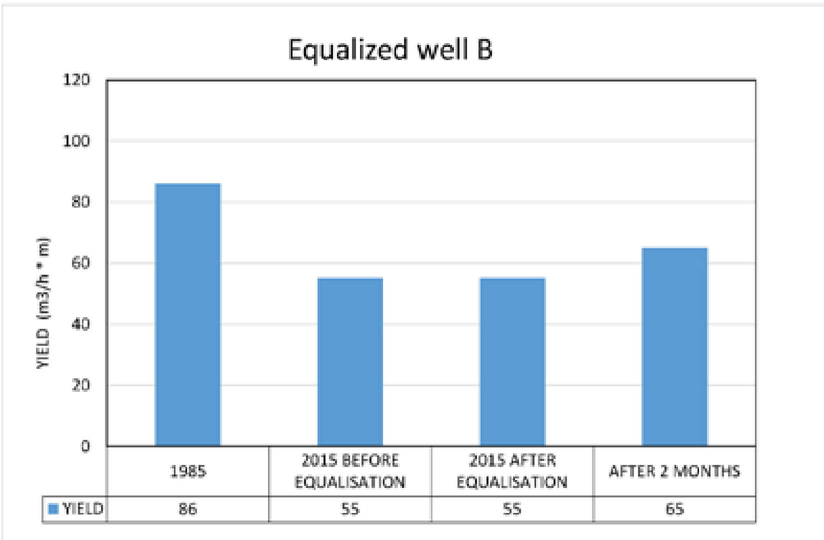

Figure 7: Changes in yield in equalised Well B in Barcelona area. Values correspond to specific tests.

Figure 8: Comparison of fouling of dataloggers in an equalised well (Well A probe, left) and in a non-equalised well (Control well A', cable and probe, right) one year after installation.

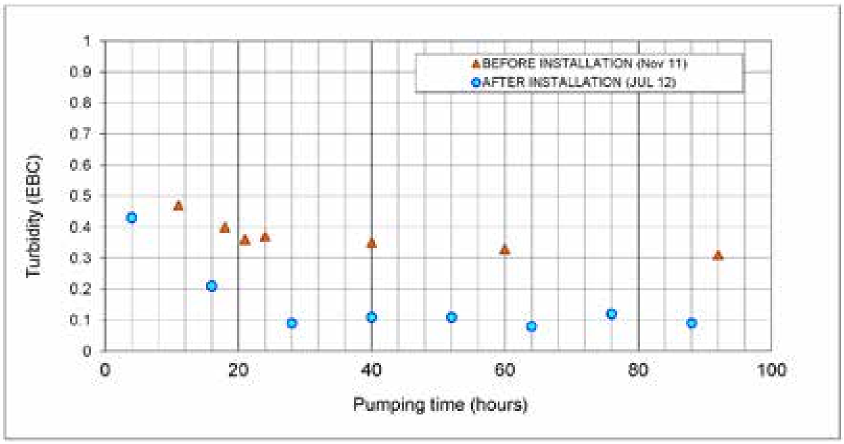

Figure 9: Comparison of turbidity in Well A before and after equalisation.

have direct observation of new incrustation on the wells and on the installed SFCD. The degree of soiling of dataloggers and communication cables installed inside the wells is an indirect way to estimate the progress of incrustation in the well. The probe and cable in Well A (installed in July 2014) remain clean one year later whereas in the control well (Well A') both probe and cable (installed in September 2014) accumulated fresh iron precipitates (***Figure 8***).

2.2.3. Observed changes in turbidity

In Well A turbidity was monitored in the pumping tests before and after installation of the SFCD. Before installation, turbidity was stable at 0.3 EBC; after installation turbidity reduced to 0.1 EBC (***Figure 9***). Sand pumping was also reduced but was not systematically measured. The parameter *Silt Density Index* (SDI) records the ability of water to clog a filter and was systematically recorded in Well A. After SFCD installation the SDI in Well A improved (***Figure 10***), showing a reduction of 0.5 units (a 25% reduction).

In equalised Well B no sand pumping or low turbidity occurred before installation. Water maintained its quality and probable improvements need a longer time to be verified.

3. Discussion

3.1 Interpretation

In both of the cases discussed an increase in yield was observed after the installation of SFCD. That increase confirms the general assumption that device flow improvement (reduction of turbulence and annular vertical flow) counteracts head losses that cause friction in the new pipe installed (Pelzer, 1991).

In the first case (Well A) we observed an initial period (from Q2 2012 to Q3 2012) of initial strong loss of yield followed by a progressive yield increase, in Q4 2012 reaching a +30% increase compared to the original level (***Figure 6***). This evolution could be related to a slow process of redistribution of the flow paths across the screen and the gravel pack. In the second case (Well B) increased losses did not occur and a moderate increase in yield (+10%) occurred after 2 months (***Figure 7***). This behaviour is probably related to a lesser degree of incrustation in the well and a shorter screen length that makes equalisation difficult.

In the first case, Well A, a 3-year data track is available (***Figure 6***). Gains persist over time, with a moderate decrease after two years. In the third year (from Q1 2014 to Q3 2015), yield is down, close to the original pre-installation values. This reduction is also observed in the control well, where a -5% loss of yield occurs, so it is not directly related to SFCD. This reduction in yield could be related to the progression of new incrustation in both wells (both Well A and the control well) or more probably to the drought period affecting eastern Spain.

Yield improvement data demonstrates that equalisation is also possible in the case of wells affected by hardened incrustations. Equalisation could also be inferred from the reduction in turbidity and SDI in Well A. The reduction in mobilisation of very fine particles must be related to a reduction in flow velocity and/or to a reduction in the vertical flow component. The persistence over time of a higher yield in Well A could be related to a reduction in the formation of new precipitates. Also the difference in the degree of fouling of the probes between Well A (clean) and the control well (soiled) must be interpreted in the same way. This point will be confirmed in the future by camera inspection of the wells.

Our results for non-rehabilitated wells seem to contradict another case study (Houben, 2006) in which the performance of two equalisation devices were compared, one in a rehabilitated well and the other in a well without rehabilitation. In that study, measured yield losses were -1.2% in the first case, and after some months a loss of -7.8% was recorded in the second. From these results the author concludes that SFCD increases well incrustation. The lack of any gain in yield after SFCD installation could indicate that equalisation had not been fully achieved. This fact could be related to well characteristics and also to the type of device used: the tail-pipe model, which has since been discarded due to poor results. The lack of equalisation made these results hard to extrapolate from.

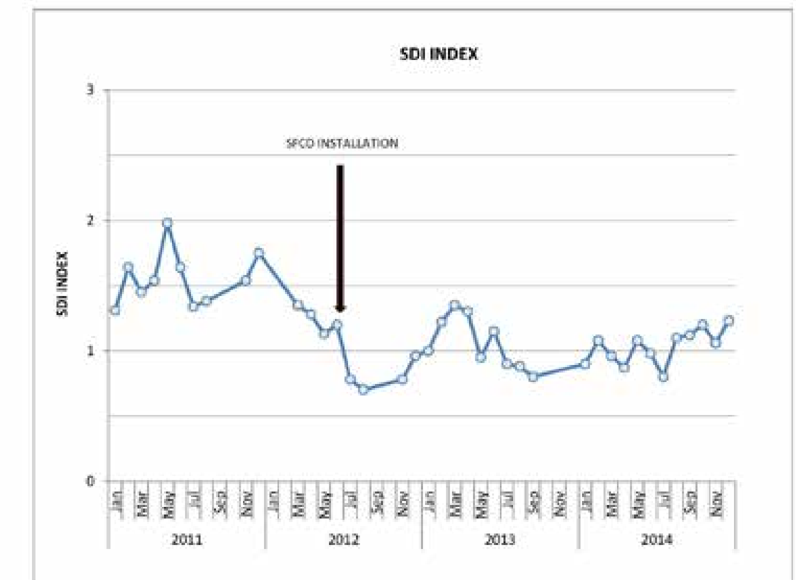

Figure 10: Evolution of silt density index in Well A: SDI is reduced after equalisation.

3.2. General points

The results for non-rehabilitated, heavily incrusted wells are in line with earlier results of increased yield linked to equalisation in new and rehabilitated wells. In the non-rehabilitated wells an initial period of temporary deterioration could occur. These initial short-lived deteriorations are interpreted as a dynamic adaptation of the well to the new flow pattern.

The results also confirm a lower mobilisation of fine particles with a reduction in turbidity and the silt density index, as well as giving clear indications of a reduction in the formation of new incrustations.

4. Conclusions

Many processes related to well ageing and the water quality of pumped water (loss of yield, sand pumping, turbidity, mineral incrustation and biofouling) are related to a high flow regime and turbulence related to a non-uniform distribution of flow in the well. Equalisation is a technique defined in the 1960s which tries to counteract the non-uniform flow pattern in the well by creating a uniform distribution of flow over the total length of the well screen. Equalisation is achieved with an SFCD device, an engineered slotted pipe inserted inside the well casing through which all the pumped water flows.

The results presented for non-rehabilitated, heavily incrusted wells are in line with earlier results of increased yield linked to equalisation in new and rehabilitated wells. In the non-rehabilitated wells an initial period of temporary deterioration could occur. Additionally, equalisation leads to less mobilisation of fine particles, with a reduction in turbidity and silt density index and a reduction in the formation of new incrustations.

As a result, we confirm that flow equalisation improves well hydrodynamics and deserves more attention in order to fully understand its potential to improve well hydraulics and mitigate ageing processes, especially those related to particle erosion and incrustation.

At present, for economic and environmental reasons, rehabilitation techniques are increasing in importance, as they are an alternative to the construction of new wells. Equalisation opens up new ground for the improvement of well hydrodynamics and new strategies in well maintenance and rehabilitation. In this technique the role of the hydrogeologist is maximised because proper equalisation requires a sound diagnosis and monitoring of the wells.

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