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REPORT

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OPTIWELLS-1 FINAL SYNTHESIS REPORT

Project acronym: OptiWells-1

by
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for
Kompetenzzentrum Wasser Berlin gGmbH

Preparation of this document was financed in part through funds provided by Veolia

VEOLIA EAU

Berlin, Germany
2012

Colophon

Title
OptiWells-1 Final Synthesis Report

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Deliverable number
OptiWells-1 D 4.1

Acknowledgement
The project team is grateful to *Veolia Eau* for sponsoring the project *OptiWells*.

We thank all involved persons at the technical divisions and research and development departments as well as the technical committee for the valuable discussions and provided information. Many thanks also to the reviewers for their constructive remarks.

Un grand merci & thank you!

Content

Chapter 1
Introduction

1.1 Scope and focus of this report

This report concludes the first phase of the project “OptiWells”, which focuses on the optimization of drinking water well field operation with respect to energy efficiency. The purpose of this document is to provide sound answers to questions that utilities and well field operators are facing. Thus, it is built as a thematically organized sequence of main questions and answers rather than an extensive manuscript-like report. In total, 13 questions are addressed in detail, while 3 main “unanswered” questions and issues are detailed at the end of this report.

The focus of this report is identical to the project’s focus: it addresses energy efficiency issues within the well field system. Thus, the main area of focus of the project lies in the interactions between the groundwater, the well, the pump and raw water pipe system (Fig. 1). Drinking water treatment, as well as water distribution is not included in this study.

This document, in combination with the other project deliverables, shall provide an overview of the potential optimizations for drinking water well fields. It shall yield both answers about saving potentials in general, and give some concrete examples from a French well field. By doing so, it shall assist the identification of solutions for an energy-efficient groundwater abstraction, and provide a basis for a sound, practical methodology for well field energy audits and assessments.

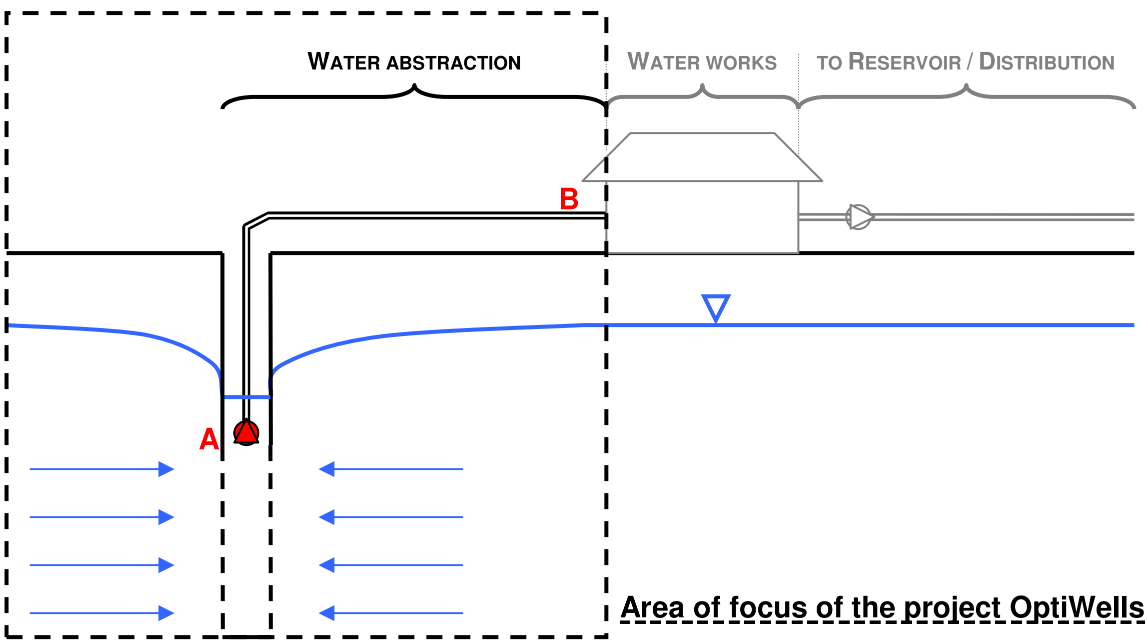

Fig. 1: Schematic of groundwater abstraction, treatment and distribution (Staub 2011).

1.2 Structure and keys to this report

This report is structured in different thematic sections: while Chapter 2 focuses on a general assessment of well field energy demand driving factors and state-of-the art energy efficiency for pumping systems, Chapter 3 focuses on the necessary data- and modeling approaches for auditing a well field.

Following symbols are used to help the user of this report finding relevant information:

- this bullet point precedes *general statements and definitions*. These are then used in the following answers of the report.
- this bullet point precedes *useful recommendations or conclusions* for well field operators. They indicate equipment, methodologies or actions that target the identification and optimisation of the well field's energy demand.
- this bullet point is related to *additional information* written in *BOXES*. In general, this information is useful to detail some particular points of interest, and it usually goes somewhat beyond the addressed question or topic.
- ➲**Q** this symbol is a *cross-reference to another question of this report*, where the corresponding issue is addressed in detail.

Chapter 2
Well field energy demand driving factors

2.1 Energy driving factors for water abstraction

1. What are the factors that influence the energy demand of water abstraction?

This project focuses on the energy drivers of *water abstraction*, or the pumping of groundwater (water treatment and energy demand from buildings being not considered here, see *BOX 1*). These include:

- the *static geometrical elevation*, i.e. the elevation that needs to be overcome in order to pump the water from the aquifer to the water works or the raw water reservoir – here, the static groundwater level is taken for reference;

- the *drawdown* at the well, induced by *aquifer losses* in the cone of depression of the water table, and *well losses* which occur when water enters the well via the screen due to local turbulences during pumping;

- the *head losses* within the pipe network that result from friction in the pipes. These are called *major* when they occur on a linear section of a pipe, and *minor* when they occur at singularities of the pipe network (valves, bends, fittings);

- the *head losses* and *efficiency losses* within the pump and motor system, which can result from inappropriate management or ageing of the equipment.

It is not possible to rank these energy driving factors from a general point of view since they depend heavily on the actual situation of the well field. However, roughly seen:

- *geometrical elevation* can be the dominant drivers for well fields in deeper aquifers (typically deeper than 20-50m): the geometrical elevation is then a “fixed” energy driver, and no large savings can be expected from sole operational changes in the well field;

- *head losses* within the pipes can be significant and be a determinant factor, especially for long networks (typically longer than 1km) Minor losses should be lower than major losses;

- *drawdown* is the most variable parameter and highly depends on the well design and age, and on the aquifer characteristics. For high pumping rates, and depending on the local conditions, drawdown can be the first driving factor;

- *head losses* and *efficiency losses* within the pump and motor system are assessed by comparing the initial and the actual pump and motor characteristics. These should never deviate significantly from each other or from typical efficiencies (➲**Q3**).

Box 1: Distribution of the energy demand for water utilities

Well fields consist of wells, pumps and pipes conveying the pumped water. A German (Plath and Wichmann 2009) and a Swiss survey (BFE and SVGW 2004) have shown that around 35% of the total energy demand was driven by fresh water pumping, regardless of the source water (groundwater/surface water) (Fig. 2).

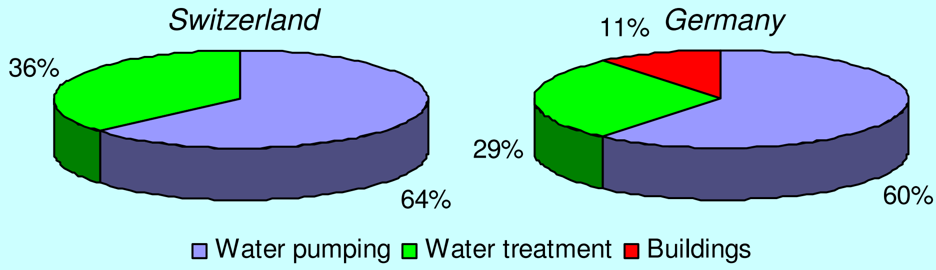

Fig. 2: Distribution for the energy demand of water utilities in Switzerland and in Germany. In the Swiss study, the energy demand of the buildings is included in the water treatment.

2. What indicators should be used to assess energy efficiency?

To assess the energy efficiency of the well field, relevant indicators need to be used either to assess the efficiency of the separate components of the system (pump, well, pipes), or to assess the overall efficiency using one unique indicator.

When using separate indicators, these should be in relation to the energy drivers (➲**Q1**):

- to assess *well performance* (i.e. the well's specific aquifer and well losses), the specific capacity Qs (m³/h·m^{-1}) should be used, which is calculated for a given Q and pumping time t, as the ratio between discharge Q (m³/h) and total drawdown s (m):

$$Qs = \frac{Q}{s}$$

To assess well performance, the well curve is also often used, defined as:

$$s = b \cdot Q + c \cdot Q^2$$

With b (h/m²) and c (h²/m^5) are the aquifer and well loss coefficients respectively. Thus, the specific discharge can be rewritten

$$Qs = \frac{1}{b + c \cdot Q}$$

- to assess *pump performance*, the pump's global efficiency η_{global} (-) or specific energy consumption E_{sp_pump} (Wh/m^3/m) can be used, the latter being more widespread. It is calculated as the ratio between the pump's electrical energy demand E_{pump} (Wh) and the pumped volume $V = Q \times \Delta T$ (m³) and the pump's Total Dynamic Head TDH (m):

$$E_{sp\_pump} = \frac{E_{pump}}{V \times TDH(Q)} = \frac{\rho \times g \times Q \times TDH(Q) \times \Delta T \Big/ \eta_{global}(Q)}{Q \times \Delta T \times TDH(Q)} = \frac{2.725}{\eta_{global}(Q)}$$

Where $\rho \times g/3600 = 2.725$ is an aggregation of constants with the conversion factors. The TDH is determined for dimensioning the pump by summing the different losses in the system (head losses j – see below – drawdown s) and to overcome the geometrical elevation between static groundwater level and the final desired water level (Δz).

- to assess the *pipe network performance*, the specific head losses per metre pipe length j_{spec} (m/m) should be calculated, and compared for each section of the network to identify weaknesses of the network (abnormal high losses):

$$j_{spec} = \frac{j}{L}$$

These indicators are the "benchmarks" to be used for an energy assessment of the respective components of the well field system.

On the other hand, a global indicator of the overall specific energy demand per cubic metre abstracted water can be used, E_{sp_global} (kWh/m^3):

$$E_{sp\_global} = \frac{E_{global}}{V} = \frac{TDH(Q)}{367 \cdot \eta_{global}(Q)}$$

This indicator is frequently used, but care should be made to the considered energy demand: if the entire pumping energy demand is accounted for, then this indicator also accounts for the energy used for water distribution (remaining part of the TDH or water pressure beyond the well field). Hence, the global specific energy demand of the well field should be used only with clear system limits.

Based on the indicators for assessing the energy efficiency, the best combination of pump and well can generally be obtained by:

- first identifying the *most efficient well* based on the $Qs=f(Q)$ curve for each well;
- then identifying the *most efficient pump* based on the $E_{sp\_pump}=f(Q)$ curve for each pump system (based for instance on the Veolia Eau DT guidelines).

However, once this "ideal" selection is made, operational constraints (e.g. availability of wells, water quality, total water demand, etc.) and site characteristics (e.g. well design, drawdown interferences) may sometimes not allow operating the most efficient combination at any given time. If the more frequent operation of the best well and pump system is not realistic, then other options for an improved well field management should be investigated, among which the optimisation of the well switchings and parallel operation.

2.2 State-of-the-art energy efficiency and potential savings

3. What efficiencies can be expected from current submersible pump systems?

Answering this question requires to compare the efficiencies of pump systems in use (or to be acquired) to the state-of-the art efficiencies of the market. This was done by scanning both the literature and the market for efficiencies of submersible pump systems. The values given here are the highest efficiencies one can expect, but in practice, these are seldom achieved because of various reasons (purchase cost too high for efficient systems, bad sizing, early ageing…).

Table 1 summarizes the key findings on state-of-the art energy efficiencies. The ranges of efficiencies given here consider Best-Efficiency Point conditions (see *Box 2*). While the upper efficiency range found in the literature is often confirmed by the market analysis, it appears that pump and motor efficiencies may be very low, resulting in global efficiencies as low as 16% for the smallest pump models (essentially 4”) (Höchel 2012).

Furthermore, the following key messages on pump efficiency can be stated:

- The overall trend is the increase of efficiency for higher flow rates, higher power classes and larger pump sizes,
- A very large deviation of efficiencies can be observed especially in the low flow rate and low power classes and for small pump sizes,
- Different pump sizes often cover the same range of operation, which means that an in-depth analysis of the system needs to be made before choosing a specific equipment.

Further improvements in pump systems, but also in the overall system, may enable important energy savings. A summary of potential savings is given in ➲**Q6**.

Table 1: Summary of current efficiencies for submersible pump systems (literature values[1], market review[2] and own calculations).

Efficiency	Depends upon	Range (liter.)[1]	Range (market)[2]
Pump efficiency η_{pump} (-)	- rated power - impeller type and diameter - load	65-85%	33-86%
Motor efficiency η_{motor} (-)	- manufacturing quality - cooling performance - load	75-90%	51-92%
Drive efficiency η_{drive} (-)	- quality of electronic components - load	95-99%	
Calculated range for η_{global} (-)	All above mentioned factors	46-76%	16-78%
Reference values for η_{global} (-)		45-73%	

[1](Staub 2011)
[2](Höchel 2012)

→ *Please refer also to D2.1 (Staub 2011) and D2.2. (Höchel 2012) for further information on the actual efficiencies of market-available pumps and motors*

4. How can pumps be operated most efficiently?

Pumps operate most efficiently at their Best-Efficiency Point (BEP – see *BOX 2*), which is characterized by a given discharge flow and delivery TDH. The BEP is unique for each pump system, except for pumps with Variable-Speed Drives (VSDs). Because of system constraints (i.e. demand profile, well field design, etc.) pumps operate away from their BEP at times and thus, *the pump's efficiency must be considered within this global system*.

Pump systems can be operated most efficiently by:

- *evaluating carefully the demand* profile and *system's characteristics* (reservoirs, pipes, valves, well curve, drawdown interferences) when choosing the pump equipment – although a slight oversizing of motors and pumps might be a conservative approach, more than 10% oversizing will result in wasted energy;
- *operating the well field at the most efficient pump association* since pumps are generally installed in parallel to supply water (well field optimisation) – at this point, it is necessary to use a model to look for the most relevant association, which might result in energy savings of up to 20% without any investment.

A summary of potential savings resulting from these improvements is provided in ➲**Q6**. When the pump systems are equipped with VSDs, it may be possible to operate pumps at different BEP, which might in turn result in significant savings compared to fixed-speed systems. This particular question is to be investigated more thoroughly in the second phase of the project.

BOX 2: OPERATION OF PUMPS AT THEIR BEST-EFFICIENCY POINT (BEP)

For an optimum pump performance (i.e. a high pump system efficiency – the least losses between the electrical input and the energy conveyed to water), pumps must be operated as closest as possible to their *best-efficiency point* (BEP). This is the pump operational scheme (delivered Total Dynamic Head, delivered discharge) where the highest pump efficiency is reached.

The goal of smart well field management is to operate most pumps in operation closest to their BEP for the majority of well field configurations.

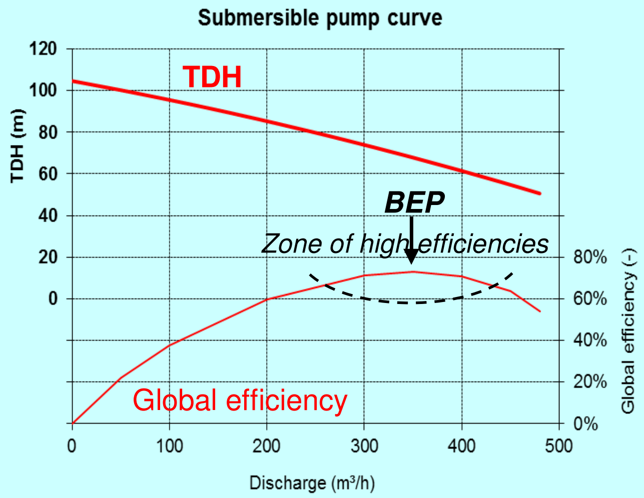

Fig. 3: Example of submersible pump curve (bold curve: head-flow curve, normal curve: efficiency curve). The zone of global efficiencies above 70% is marked (dashed line).

5. What are the possible technical improvements for pump systems?

Here, only technical or operational improvements at the pump level are discussed. These include:

- the improvement of the *pump design* by improvements in the impeller, blade and casing design (shape, size ratios), the choice of new, smoother components and / or coating the pump in order to minimize hydraulic resistance and head losses in the pump impeller and casing. Up to 2% energy savings can be obtained from such improvements;
- the improvement of the *motor design* (high-efficiency motors) by optimizing the stator windings, applying high-quality components for bearings, lubrication and sealing or optimizing the motor cooling;
- the minimisation of *hydraulic losses* in the vicinity of the pump by adapting the hydraulic equipment, for instance removing unnecessary check-valves, unnecessary bends, or installing smoother hydraulic bends and valves.

A summary of potential savings resulting from these improvements is provided in ➲**Q6**.

6. Overall, where do the largest energy saving potentials lie?

Based on the considerable review of literature, and on the workshop organized with the pump manufacturers, Table 2 summarizes the potential energy savings for pump, motor, performance or other systems adaptations on a well field. The values are given from the literature and/or from operators' personal communication. They represent average saving potentials but do not consider cases with obvious maladaptation of original design, where of course huge savings can be obtained. The savings are given in percentage points and may not be cumulative.

→ *Please refer also to D2.1. (Staub 2011) for further information on the possible improvements of pump and motor technology*

Table 2: Summary of energy saving potentials (after (Shiels 1998; BPMA 2002; Schofield 2005; Kaya, Yagmur et al. 2008; Haakh 2009; Sustainability Victoria 2009; Boldt 2010), with estimates from current study).

Nature of improvement	Expected savings	Cost level*	Payback time**	Remarks
Improvement of pump and motor				
Improved pump technology	1 – 5%	€ - €€€	🕘🕘	If integrated in pump system renewal costs, the additional cost is moderate
Improved motor technology	1 – 3%	€ - €€€	🕘🕘🕘	
Better correspondence between pump & motor	2 – 4%	€€	🕘🕘	Very site-specific
Performance adaptation				
Impeller trimming	0 – 20%	€	🕘	Only permanent downgrading
Adaptation of impeller stages / Modular shaft	0 – 10%	€€	🕘🕘	Few references, motor to be adapted
Variable speed drive to replace throttling	-10 – 30%	€€	🕘🕘	Very site-specific, not for high static head
System general improvement				
Pump cleaning	0 – 12%	€	🕘🕘	Also increases the pump lifetime
Pipe cleaning	0 – 10%	€€	🕘🕘	Few references, depends on pipe age
Smart well-field management	10 – 20%	€	🕘	Few references, site-specific

*€: *low*, €€: *medium*, €€€: *high*

**🕘: *short (1 year)*, 🕘🕘: *medium (2-5 years)*, 🕘🕘🕘: *long (5-10 years)*

Chapter 3
Data analysis and well field modelling

3.1 Data quality, data acquisition and analysis

7. What data shall be acquired when performing a measurement campaign?

The goal of an energy audit is to record actual data and to compare it to manufacturer and logged data. Since the pumps are the energy-demanding equipment on well fields, actual pump head-flow and efficiency curves need to be measured as part of measurement campaigns. To do so, pressure, discharge and energy demand need to be measured using the following equipment (Fig. 4):

- *flow meters* (Q) to be positioned ideally on the horizontal pipe within the well chamber of each of the wells to test configurations with several wells working in parallel (for logging disturbance-free discharges, see ➲**Q8**). If only one flow meter is available, it may also be positioned at the water works in order to avoid frequent installing and de-installing, but then configurations with several wells in parallel may be very delicate to interpret;
- *pressure sensors* (P) to be positioned one at the water works and one at each well (for logging disturbance-free pressures, see ➲**Q8**). It is essential that pressure sensors are installed as close as possible to the well head since they need to assess the pressure directly behind the pump;
- an *amperemeter* and *voltmeter* (I, U) to be installed on the electric power supply of the pumps at the well heads to calculate their instantaneous power consumption.

Pressure and discharge are used for the head-flow curve, while pressure, discharge and energy demand are used for the pump efficiency curve, and the differential pressure between well and water works is used in combination with the discharge for the pipe's head loss curve. With this equipment, it is possible to log all the data required to derive the head-flow and efficiency curves for the pump systems. A protocol for a site measurement campaign is proposed in ➲**Q9**.

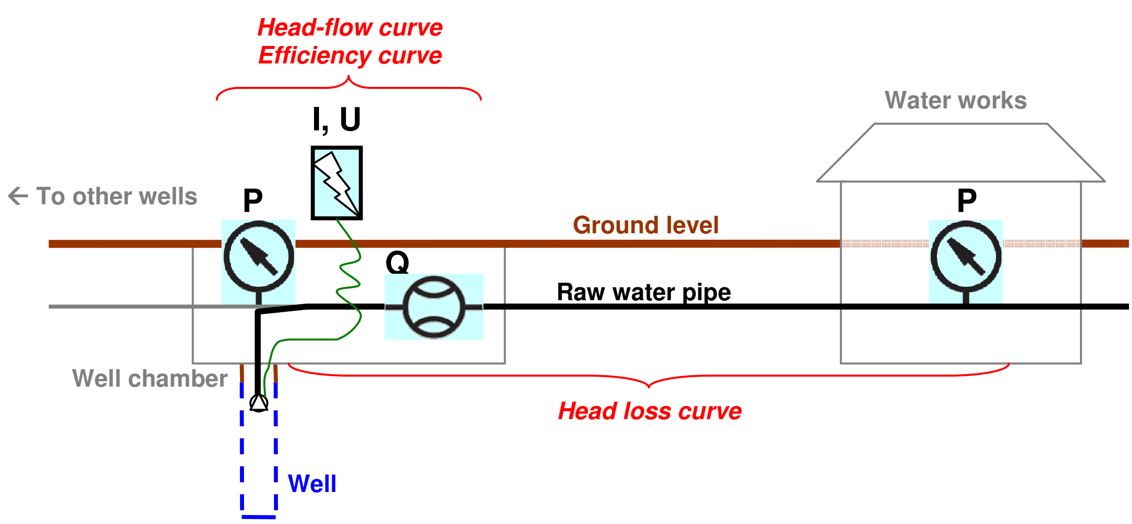

Fig. 4: Proposed installation of sensors for a site measurement campaign as part of an energy audit.

8. What specific care must be given to the quality of logged or recorded data?

Data can be either logged on the long term by the well field operator, or recorded during a measurement campaign on site (energy audit). In either case, data quality is essential to yield exploitable results.

In case of logged data, long series of parameters are to be recorded. To ensure the highest possible data quality,

- *appropriate logging frequencies* should be used. For instance, measurements *every minute* or *every ten minutes* seem reasonable, less than one measurement per day is generally useless, or will result in approximations. However, the required measurement interval depends on the final projected use of the data.
- *appropriate sensors* must be installed. All sensors intrinsically have measurement deviations, with some techniques being more accurate than others (see *BOX 3*). The last calibration date should also be considered, as some sensors can drift out of calibration quite rapidly.
- if possible, *sensors measuring or providing physical values at a given time interval* should be preferred to status loggers (which only record status or parameter changes). Loggers recording only status changes induce more risks of cumulative errors if one status change is not detected (i.e., if one status is wrongly logged, all following statuses might be inversed).

The objective of a measurement campaign during a site audit is to provide additional data to model the well field more accurately. In this specific case, additional sensors are brought to the site and installed at various key points of the well field (➲**Q7**). To ensure the highest reliability of data, the sensors must be installed properly on the pipes and/or in the wells (see *BOX 4*), and any disturbance condition must be carefully monitored, for instance excessive drawdowns, cavitation noises, logger or pump failure. Here again, it must be noted that the data recorded from built-in sensors – provided they are well calibrated – is generally speaking more accurate.

BOX 3: ESTIMATING UNCERTAINTIES: EXAMPLE OF DISCHARGE MEASUREMENTS

Discharges in water pipes may be, among others, measured by UltraSound (US) flow meters or Magnetic Induction Discharge (MID) meters. Due to the use of a completely different technology, the measurements may deviate by up to 5-10% between both devices. For clear water, MID meters are technically more accurate (Bauer 2005). Devices permanently installed on well heads, pipes or at the pump station should also be used as references, since they are usually better installed than clamp-on discharge meters.

Box 4: Installation of devices on pipes: the example of pressure and discharge sensors

Pressure sensors and flow meters yield essential information for the modelling of the entire well field system. They need to be installed on pipe sections with the less possible hydraulic disturbances - at least three to five times the diameter away from valves, bends and fittings. Fig. 5 shows an example where a pressure sensor was installed too close to a bend.

The correct installation of devices is important to guarantee non-turbulent flow conditions. Furthermore, these devices only work in fully-pressurized pipes, i.e. pipes filled with water. Thus, the initial measurements just after starting the pump represent transient measurements, which are not accurate (see also ➲**Q9**).

Fig. 5: Example of installed pressure sensor which is located too close to the bend (the site configuration did not enable to install it elsewhere).

9. What logging protocol should be followed for a measurement campaign?

The goal of a measurement campaign on wells is to acquire current accurate data for the audited wells. To do so, loggers are installed at various points (➲**Q7**) and need to record data at a very short time interval, which ideally *should be down to 1 second*. Hence, *the detailed protocol depends on the logging capacity of the logging devices* which may well be a limiting factor for the measurement campaign.

Usually it is not possible to log for more than several hours using a sampling frequency of one measurement per second. If the maximum logging time is *around one hour*, the following protocol can be followed, with possible adaptations to local contexts (Fig. 6):

- initialisation of the measurement equipment and begin of logging (pump off);

  Proposed duration = max. 1 minute.

- start of the pump with throttling valve or flow-regulating device half to fully open (pump on at high discharge rates). During this phase, the flow in the pipe is usually transient, e.g. because some pipes may not be filled with water;

  Proposed duration = 8-10 minutes (absolute time 8-11 minutes).

- the flow-regulating valve is closed to have zero discharge, which is used as a first measurement on the head-flow and efficiency curves;

  Proposed duration = 4-5 minutes (absolute time 12-16 minutes).

- then, stepwise increase of the discharge with the help of the flow-regulating valve every 4-5 minutes. Every time, a new point on the head-flow and efficiency curves as well as on the head loss curve can be logged

  Proposed duration = 4-5 minutes each /
  40-50 minutes in total (abs. time 52-66 min).

As stated earlier, while installing the devices, specific care must be given to the conditions of installation for disturbance-free measurements (➲**Q8**). All loggers should also be tested prior to the final logging, and the quality of the logged data should be verified.

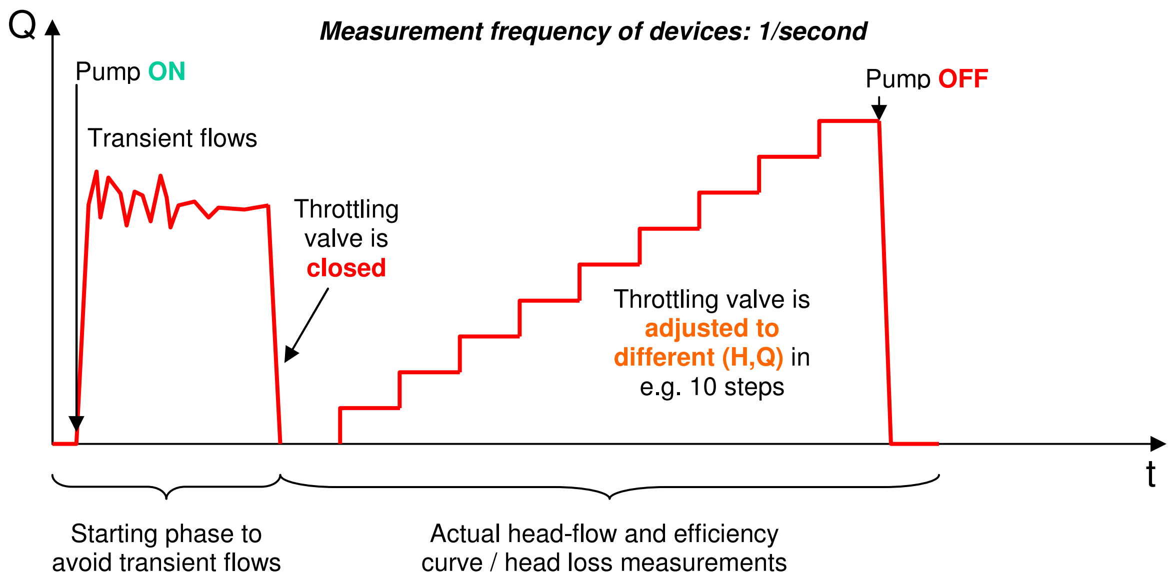

Fig. 6: Pump flow versus time for the proposed test protocol for a site measurement campaign as part of an energy audit.

3.2 Well field modelling

10. What are the global data requirements for well field modelling?

In general, it is possible to model a well field using a limited amount of data by using some basic characteristics and assumptions that are compulsory for running the simulations. However, the more data is available, the better the model calibration and predictability. If a local or regional groundwater model is available, it can be used to better consider drawdown induced by the aquifer.

On the other hand, to perform an extensive statistical analysis and modelling of the well field, several series of data are required, if possible for a longer time span (e.g. evolution of drawdown, operating hours, discharges, energy demand, pressure at well head). Both for a statistical (data-driven) approach and a physical modelling (process-driven) approach may be relevant, depending on the required results (➲**Q11**).

Table 3 summarizes the required data for the respective approaches. *Geometrical data*, *basic groundwater data* as well as *pump data* is required in any case. For a more detailed calibration, some precise data on the well field operational parameters may be essential. It should be noted that some current data can be measured during a site audit, if there is no data series available on site (➲**Q7**).

Table 3: Summary of data requirements for well field data analysis and modelling. Requirements indicated in brackets may contribute to more accurate results, but may not be absolutely essential.

Type of data	Minimum data for basic well field model	Minimum data for a detailed calibration	*Minimum data for an extensive statistical model*
Geometrical data (elevations, lengths)	✔	✔	✔
Initial **pump curves** (from manufacturer)	✔	✔	(✔)
Static and dynamic **water levels** / or well curves	✔	✔	✔
Current **pump curves** (from measurements)	(✔)	✔	
Pipe data (material, equipments, length)	(✔)	✔	
Aquifer characteristics	(✔)	✔	
Operating hours		(✔)	✔
Discharge per well		(✔)	✔
Energy demand per well		(✔)	✔
Pressure at well head or elsewhere		(✔)	(✔)
Hydrogeological model		(✔)	

11. What can modelling offer compared to a data-driven approach?

While data analysis is relevant to discuss the current status of a well field, it is intensive in minimum data requirements (➲**Q10**) and it cannot predict situations which are different from the ones observed. For instance, if the analysed data concerns a given operation scenario, and the latter is changed, data analysis will not be able to predict the impacts of this scenario change.

Thus, *predictive process-driven modelling* is necessary in most cases to predict the impact of a given operational choice (*Box 5*).

To ensure that this modelling is accurate, it is necessary:

- to detain a *reasonable minimum amount of data* coming from a site audit in order to perform a sound calibration of the model;
- to include *all known physical phenomena* in the modelling, i.e. well, pump and network characteristics, drawdown patterns, demand patterns etc.

Since well field are complex structures, with several interactions, *it is crucial to couple the distinctive models in an integrated manner* and to calibrate the resulting model accurately.

However, taking into account all phenomena is time-intensive and may lead to an over-parameterisation of the model, with too many parameters to calibrate the model, or too many assumptions to be made. An optimum between under- and over-parameterisation needs to be found, for instance by including only the major drivers of the energy demand for the given well field (➲**Q1**).

Box 5: Data-driven and Process-driven approaches

When auditing a well field site, it is possible to have a data-driven "black-box"-approach, or a process-driven "physical" approach. Data-driven approaches are based on statistical analysis of recorded data, whereas process-driven approaches rely on physical (here hydraulic) equations, solved using entered system characteristics and assumptions. The range of analysed data limits the prediction capacity of data-driven models, while a well-calibrated and well-defined process-driven model may predict the impact of various scenarios.

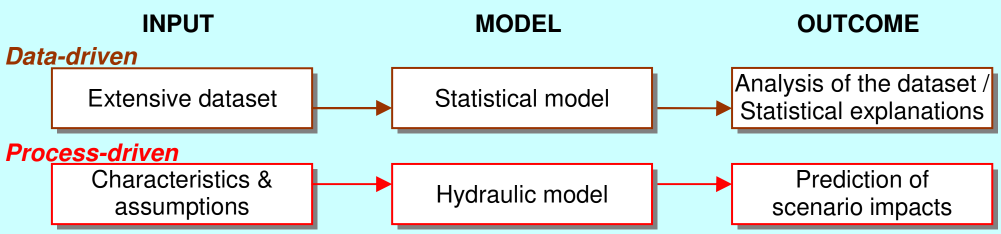

Fig. 7: Schematic representing the data-driven and process-driven approaches.

12. What physically-based models should be preferred and for what context?

To date, *there is no commercially-available tool to simulate the entire well field system and perform its optimisation*. However, several models may be used to simulate the hydraulic behaviour of pipes and pumps in a well field. Among these are,

- For a *basic approach*, MS Excel or any comparable spreadsheet program may be useful to calculate flows and heads for simple systems. These can encompass up to three different pump patterns with a simple network architecture. Excel is not flexible when it comes to modify the pump statuses or to implement new objects.

- For *more complex networks*, EPANET is an open-source hydraulic network modelling program (*Box 6*). The program covers a wide range of possible hydraulic objects, though not integrating the groundwater explicitly. EPANET can be controlled easily from a numerical programming shell to interact with other programs.

- More sophisticated programs such as WaterCAD, InfoWorks WS, or Flowmaster for instance can be used instead of EPANET. The main improvement is the interface and user-friendliness, however, these programs usually have the same limitations as EPANET (namely that the groundwater cannot be explicitly accounted for, and that calculations for complex networks are time-consuming), and are not open-source.

Since there is no integrated solution for modelling all components of a well field, the possibility to interact with other sub-models is very relevant, and here EPANET was chosen to compute hydraulic results at the well field. An investigated possibility is to use EPANET in combination with MS VBA in an MS Excel environment, in which the drawdown model could be implemented. Furthermore, this could enable to perform several steady-state simulations in a row and to recreate “unsteady conditions” (➲**Q13**).

Box 6: The pipe network model EPANET

EPANET is an open-source modelling software that enables to calculate discharges, head losses, pressures and costs for a pressurized drinking water network. It considers pumps, reservoirs, pipes and various types of valves, bends and fittings (Fig. 8). It is also possible to integrate drawdown in an indirect way.

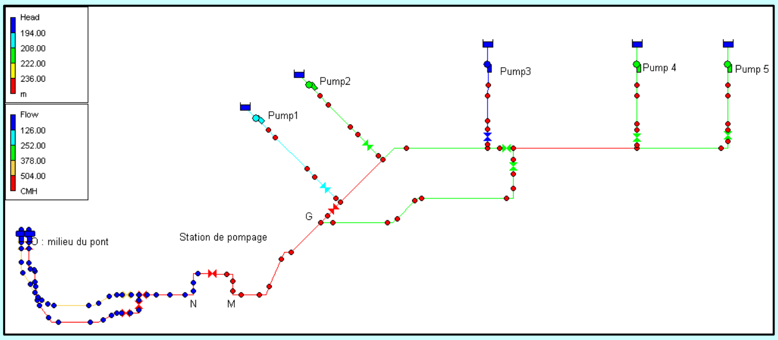

Fig. 8: Screenshot of the water network modelling program “EPANET” (5 wells, 5 pumps).

13. How can a model coupling be made and using what tools?

Coupling models can be basically seen as the *coordinated use of several models to solve a complex problem*. It is more than the pure aggregation of different models, because the modelled components or objects often interact in a dynamic way – such as the drawdown and the head in the pipe network, in our case – making thus the use of a global "programming shell" necessary to manage the interactions between the models.

For the analysed system (aquifer, well, pump and pipe network – see Fig. 1), it is proposed to perform the conceptual coupling of a *drawdown* and a *pipe network* model by using the two characteristic variables:

- hydraulic head H (metre water column),
- operational discharge Q (m³/h) (Fig. 9).

In addition to this physical coupling (used to solve the hydraulic model), a coupling needs also to be made with an optimization routine, in order to choose the most energy-efficient or cost-efficient hydraulic scenario and to select the best well field management option. For this study, the characteristic variables specific cost C_{sp} (€/m³ or €/year) and specific energy demand E_{sp} (kWh/m³, kWh/year or Wh/m³/m) are considered and used as entry variables for optimisation.

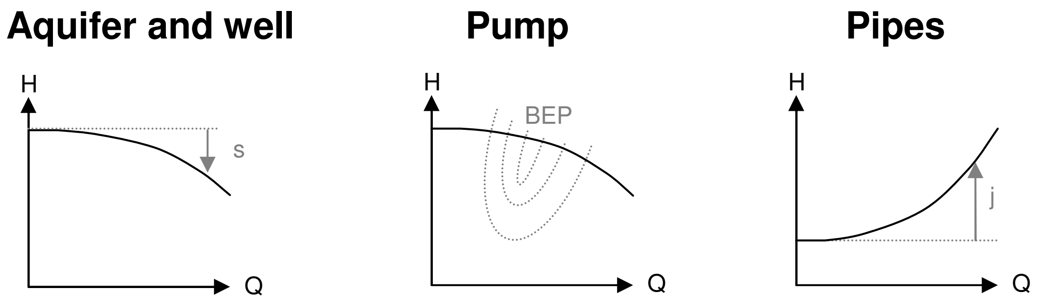

Fig. 9: Schematical curves for the system's characteristic variables, H and Q.

As a result of the investigations and experience gained in Optiwells-1 we propose to use following tools for a coupled model: MS Visual Basic for Applications (VBA) for the coupled modelling shell (an object-oriented developing tool in Visual Basic which is implemented in MS Excel), EPANET and a drawdown model for the hydraulics (see also ➲**Q12**), and the statistical tool R for the optimisation approach (Fig. 10).

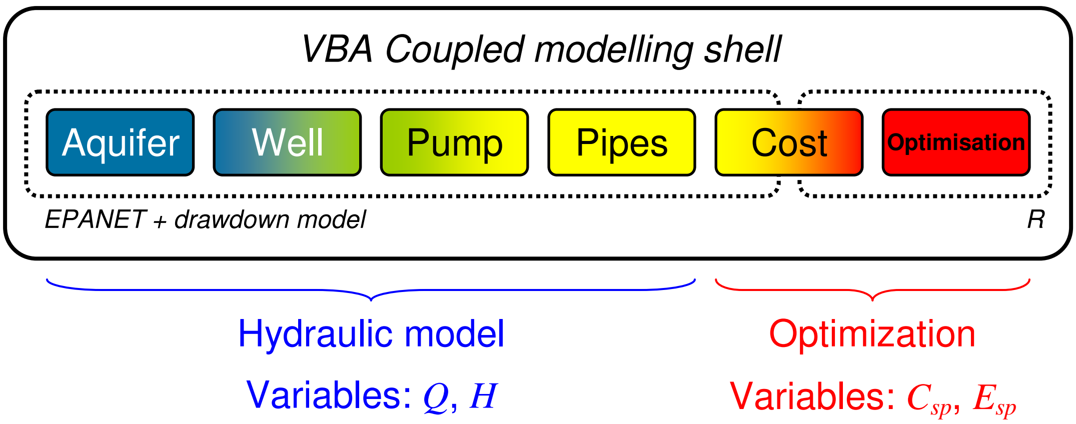

Fig. 10: Concept for a coupled modelling shell and considered sub-models.

Chapter 4
Open questions and conclusions

4.1 Open questions and challenges for the project second phase

14. What is the influence of hydrogeology and neighbouring wells?

This question is an essential question for the groundwater approach. In this study the drawdown was simulated in a relatively simple manner, since only steady-state drawdown values were considered, derived from the results of pumping tests. Especially in case of frequent switchings steady-state drawdown values may not be the most relevant ones to consider.

Furthermore, wells interfere with each other due to the influence of drawdown even at distant places (cone of depression). If several wells are in operation, the drawdowns may be cumulative at a given well, inducing additional aquifer losses leading to additional pumping energy. This needs to be quantified in the project's second phase, since it may be a major contributor to the energy demand if wells are located close to each other and if aquifer is not very transmissive. An easy field test to identify these interactions is to measure the water tables in non-operating neighbouring wells while one well is in full operation.

15. What is the influence of ageing on the well field's energy efficiency?

Ageing generally affects wells, pumps and pipes by decreasing their efficiency or creating additional head losses due to deposits, blockages or local failures. Although this is generally acknowledged, ageing is relatively difficult to quantify due to the various processes involved, and to the complexity of environmental conditions leading to ageing.

In this study, ageing was not accounted for in the prospective modelling. A comprehensive and quantified approach of ageing would however ideally need to be taken into account in a complex well field optimisation model, in order to support smart investments when confronted to specific environmental conditions.

The issues pointed by these last two questions could be "covered" by regularly redefining the specific discharge (Q_S) curve (➲**Q2**). The shape of this curve tightly depends on the interference of the neighbouring wells and the condition of the well structure.

16. In which configurations may a VSD be relevant?

The potential for installing a Variable-Speed Drive (VSD) was not evaluated in detail for the studied well field, and this technology was only investigated briefly in the first work package (➲**Q6**). Generally, VSDs may be relevant for several configurations, especially when demand and/or boundary conditions of the system show significant changes (e.g. daily variability). VSDs may also have positive side-effects on ageing (➲**Q15**) due to reduced switching, which are, to now, not very well quantified, but currently investigated within the KWB project WELLMA-2. For the second phase of the project it is proposed to develop a decision-tree to support the relevant implementation of VSDs, thanks to exchanges with pump manufacturers and support from site studies.

4.2 General conclusions and recommendations

This study has shown the potentials for energy savings in drinking water abstraction, which can significantly reduce the overall costs as well as the carbon footprint of utilities. Since there is a growing concern on cost and environmental issues, it should be acknowledged that through smart well field operation and investment in improved pumps, significant savings may be achieved. More than giving quantified results on a single case study, the purpose of this first project phase was to demonstrate the feasibility of the savings, but also the relevance of the followed methodology and tools.

Globally, the energy and cost saving potential for drinking water well fields lies in:

- the improvement in well field management (smart well field operation, ~30% as maximum saving potential, site- and configuration-specific);
- the improvement of the system maintenance and management (~20% as maximum saving potential, depending on current maintenance scheme).
- the improvement in pump and motor technology (~8% as maximum energy saving potential);

The optimization potentials of a given well field will however highly depend on the site characteristics themselves, on the demand and on the operation and maintenance history. The improvement of pump technology will yield, even optimistically seen, an efficiency improvement of up to 10%, which is the potential “theoretical limit” (EC 2003). For further improvements, it is necessary to consider solutions that go beyond the pump system. Even the most efficient pump in a system that has been wrongly designed is going to be inefficient. Moreover, an efficient pump in an inefficient well is pointless. Hence, a global approach of the groundwater abstraction system is required, as the pumping system needs to be adapted to the well/aquifer characteristics, and not the other way round.

Finally, one should not forget the primary objective of water abstraction, which is satisfying a given water demand, thus, the safety of drinking water production prevails over energy efficiency. The proposed coupled modeling and optimization tool is still not user-friendly enough to be used by utilities. Further improvements are required in the project second phase to help well field managers to efficiently support operational decisions.

Chapter 5
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