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# Step-drawdown tests in exploitation wells for thermal and mineral water – Case study from Slovenia

## Črpalni preizkusi v korakih v eksploatacijskih vodnjakih za rabo termalne in mineralne vode – študija primera Slovenije

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*Ključne besede:* črpalni preizkus v korakih, mineralna voda, termalna voda, učinkovitost vodnjaka, Slovenija

### Abstract

A comparative analysis of step-drawdown tests was performed in order to estimate the well performance in Slovenian thermal and mineral water wells. Tests were performed in 30 wells, each having its own maximum production rate determined in the concession decrees. The main focus of well performance analysis, using graphical analysis of the Jacob approximate equation, was to estimate the adequacy of the wells production rate as well as to identify possible changes in the technical status of the wells over years. 5 of total 30 wells were not included in the analysis due to technical issues during test performance. Well performance analysis includes the calculation of nonlinear well losses related to turbulent flow and linear head loss (aquifer and well) assumed to be related to laminar flow. Results indicate that the ratios between nonlinear well losses and linear head (well and aquifer) losses, in this paper referred as laminar losses, are from 6.9 % to 97.4 %. Laminar losses parameter suggests, all investigated wells were classified with either good (11 wells), medium (7 wells) or poor (7 wells) performance. The addressed analysis represents a very important basis for further thermal and mineral water extraction, e.g. optimizing the maximum allowed production rate as granted in concession decrees and diagnose potential changes in the technical status of each well.

### Izvleček

Za oceno učinkovitosti eksploatacijskih vodnjakov za rabo termalne in mineralne vode je bila izvedena primerjalna analiza črpalnih preizkusov v korakih. Črpalni preizkusi v korakih so bili izvedeni v 30 vodnjakih, pri čemer je bila najvišja količina črpanja v posameznem vodnjaku enaka najvišji količini, ki izhaja iz koncesijskih uredb. Glavni namen analize učinkovitosti vodnjakov, ki je temeljila na Jacobovi grafični metodi obdelave črpalnega preizkusa v korakih, je oceniti in preveriti ustreznost sedaj dovoljenih količin črpanja, hkrati pa tudi določiti morebitne spremembe v tehničnem stanju vodnjakov. Pet od skupno 30 vodnjakov, zaradi tehničnih težav med samo izvedbo črpalnega preizkusa v korakih ni bilo vključenih v analizo. Sama analiza učinkovitosti vodnjakov temelji na izračunu nelinearnih izgub vodnjaka kot posledica turbulentne komponente toka in linearnih tlačnih izgub (vodonosnika in vodnjaka), privzetih kot posledica laminarne komponente toka. Rezultati analize kažejo, da so razmerja med nelinearnimi in linearnimi izgubami, ki so v tem članku opredeljena kot laminarne izgube, med 6,9 % in 97,4 %. S pomočjo parametra laminarnih izgub smo preiskane vodnjake ocenili z dobro (11), srednjo (7) ali slabo (7) učinkovitostjo. Obravnavana analiza predstavlja zelo pomembno podlago za nadaljnje črpanje termalne in mineralne vode, npr. za morebitno optimiziranje najvišje dovoljene količine izkoriščanja, ki izhajajo iz koncesij, in za diagnosticiranje potencialnih sprememb v tehničnem statusu posameznega vodnjaka.

## Introduction

In Slovenia, many mineral and thermal water resources are found (Lapanje & Rman, 2009), however their management was not very efficient in the past (Rman et al., 2011, 2015). Thermal water is defined in the Water Act (Official Gazette, Nos. 67/02, 2/04 – ZZdrI-A, 41/04 – ZVO-1, 57/08, 57/12, 100/13, 40/14, 56/15 and 62/20) as a groundwater which exceeds the temperature of 20 °C at its outflow to the surface. Three types of low-temperature thermal systems occur here: warm spring systems in fissured and karstified carbonate aquifers, aquifers in fissured carbonate and metamorphic rocks in basement rocks below sedimentary basins, and intergranular aquifers in sedimentary basins (Lapanje & Rman, 2009). Two thermal water regional flow systems are exploited by several users: mineral and thermal water bearing sandy aquifers in the Mura-Zala sedimentary basin in NE Slovenia and thermal water in dolomite aquifers in the basement of the Krško-Brežice sedimentary basin (Rman et al., 2019). Mineral water is defined in the Water Act (Official Gazette, Nos. 67/02, 2/04 – ZZdrI-A, 41/04 – ZVO-1, 57/08, 57/12, 100/13, 40/14, 56/15 and 62/20) as groundwater which fulfils the written criteria and originates from a well, spring or capture but the criteria are not listed anywhere. In hydrogeological practice, we usually classify mineral waters as the ones having more than 1 g/l of total dissolved solids or more than 250 mg/l of $CO_2$. Confusion is often caused because the term natural mineral water is also used in legislation. It is used for bottled groundwaters according to the Rules on natural mineral water, spring water and table water (Official Gazzette, Nos. 50/04, 75/05 and 45/08 – ZKme-1), which do not have a unique hydrogeological classification similar to aforementioned. In this paper, we use expression mineral water for a group of wells which produce waters for beverages. most of them are enriched in $CO_2$ and therefore also have higher mineralization.

It would be expected that a reliable resource assessment is performed prior to the start of exploitation but, in practice, the approach was rather different in the past. At sites with decades-long exploitation of mineral and thermal waters most water-producing objects (mostly wells) were not properly and/or systematically tested on capacity, if tested at all. No systematic research has yet been conducted on possible differences in hydraulic properties of production wells tapping intergranular or fissured aquifers. Average age of more than half of producing thermal and mineral water wells is above 30 years (Rman & Lapanje, 2018). In some cases, operational issues such as mineral precipitation, corrosion, gas eruptions and silt clogging are also reported. As it is necessary to determine whether the reasons for some noticed changes in well capacity are in deterioration of the aquifer state or the object itself (Kralj et al., 2009; Rman, 2014; Szőcs et al., 2013), it is necessary to systematically monitor well's efficiency and to timely implement measures for preventing possible deterioration.

Considering the above, a methodology for comparison of well's performance over a lifetime is reasonable to be applied systematically in order to, in the event of a change, identify the need for well revitalization or improvement of the aquifer's status. This approach was identified also by the Slovenian Ministry of the Environment and Spatial Planning which implements decrees on the concession for the use of thermal water according to the Water Act (Official Gazette, Nos. 67/02, 2/04 – ZZdrI-A, 41/04 – ZVO-1, 57/08, 57/12, 100/13, 40/14, 56/15 and 62/20). There is a difference between the ones issued prior to the year 2015 (e.g. Official Gazette, No. 125/04) and afterwards (e.g. Official Gazette, Nos. 103/15 and 14/18). The newest Decrees contain more extensive monitoring requirements. Continuous monitoring of groundwater level, temperature and production rate, waste water temperature and quantity, plus regular water chemical and isotopic composition have to be determined annually. When annual abstraction at a site exceeds 200,000 $m^3$/year monitoring data have to be online, daily transmitted to the database of the Slovenian Environmental Agency. Requirements include also systematic measurements of hydraulic characteristics of production wells (efficiency and specific capacity) in the period of every 3 and 6 years.

A single-well step-drawdown test, also called step test, is used to quantify well performance criteria, such as well efficiency and its specific capacity, and can provide an estimate of the maximum yield of the well (Abdalla & Moubark, 2018). Therefore, the step-drawdown test is one of the most frequently performed types of pumping test, particularly in the case of single well (Kawecki, 1995). Jacob (1947) was the first to present the conceptual formulation of step-drawdown test. Since that time, a number of articles were published in order to refine interpretation (Rorabaugh, 1953; Bierschenk, 1963; Lennox, 1966; Mogg, 1969; Sheahan, 1971; Birsoy and Summers, 1980; Gupta, 1989; Helweg, 1994 and Kawecki, 1995). Those interpretations are based on graphical procedures, however some published papers on numerical analysis are also published (e.g. Louwyck et al., 2009).

In this paper, the summary results of testing of 30 mineral and thermal water wells in Slovenia are presented, which were performed in years from 2016 to 2018. The Jacob (1947) graphical method for step-drawdown test interpretation in controlled and variable abstraction conditions was used as described by Kruseman and De Ridder (1990) as it provides an approximation of specific capacity e.g. well capacity versus measured drawdown at different abstraction stages. The difference among mineral and thermal water wells, and fissured and intergranular aquifers was investigated. Appropriateness of the maximum allowed production rate as granted in concession decrees was compared to currently calculated value considering the actual technical status of the well.

## Methodology

### Theoretical background

#### Performance

*Analytical approach*

In is very likely that in the immediate vicinity of the well, due to nature of groundwater flow there may be a deviation from the Darcy law describing linear movement of fluid flow through a porous media. The deviation can be reflected as larger drawdown in producing well as the theoretical model could predict. It is assumed that the measured drawdown in a pumped well consists of two components: aquifer losses (linear) and well losses (linear and non-linear). For an ideally confined system with radial flow to well with constant discharge with no well losses the drawdown $s$, using Theis (1935) nonequilibrium formula is given by:

$$s(r_w, t) = \frac{Q}{4\pi T} W(u) \tag{1}$$

where $Q$ is the discharge, $t$ is the time and $r_w$ is the true radius of the pumped well, $T$ is aquifer transmissivity, $W(u)$ is the Theis well function (Theis, 1935) and:

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + \ldots \tag{2}$$

where

$$u = \frac{r_w^2 S}{4Tt} \tag{3}$$

where $S$ is the storage coefficient. It was recognized that the terms beyond ln($u$) in the expanded series of the well function $W(u)$ can be neglected if $u$ is sufficiently small (i.e. large values of elapsed time). Jacob (1950) suggested an approximation of $u < 0.01$. When $u$ is small the well function may be approximated by:

$$W(u) \cong \ln \frac{2.25Tt}{r_w^2 S} \tag{4}$$

Substituting (4.) in (1.) gives:

$$s(r_w, t) = \frac{Q}{4\pi T} \ln \frac{2.25Tt}{r_w^2 S} \tag{5}$$

Considering equation (5), the total well loss is than given by:

$$s_w = s(t) - s(r_w, t) \tag{6}$$

where $s_w$ is the total well loss and $s(t)$ is the observed drawdown in the pumped well at time $t$.

Assuming that total drawdown in the well is a sum of $s_1$, $s_2$ and $s_3$ as suggested in Figure 1 the proposed model would then be (7):

$$s(t) = B_1(r_w, t)Q + B_2 Q + CQ^2 \tag{7}$$

where $B_1$ is the linear aquifer loss coefficient occurring in the area where the flow is laminar (T/L$^2$), $B_2$ is the linear well loss coefficient (T/L$^2$), $C$ is the non-linear well loss coefficient in T$^P$/L$^{3P-1}$ and $P$ is an exponent of the well discharge (note: T is unit of time and L unit of length). All three coefficients are derived from the observation of the flow towards well. These are laminar and turbulent flow, or a combination of both. Laminar losses usually occur away from the boreholes, where the velocities are low, which is the case for linear aquifer losses. On the other hand the linear well losses occurs relatively close to well bore in the damage zone of the aquifer (e.g. caused by drilling), where the hydraulic conductivity is usually considerably lower than that of the aquifer. The larger the hydraulic conductivity difference, the more important is the value of the linear well losses within the parameter $B$. Although some authors (e.g. Williams, 1985) suggested that head losses through the damage zone are generally laminar, the arguments for such estimation are rather uncertain.

In practice if the »independent« aquifer properties are unknown, it is seldom possible to take $B_1$ and $B_2$ into account separately (Kruseman and

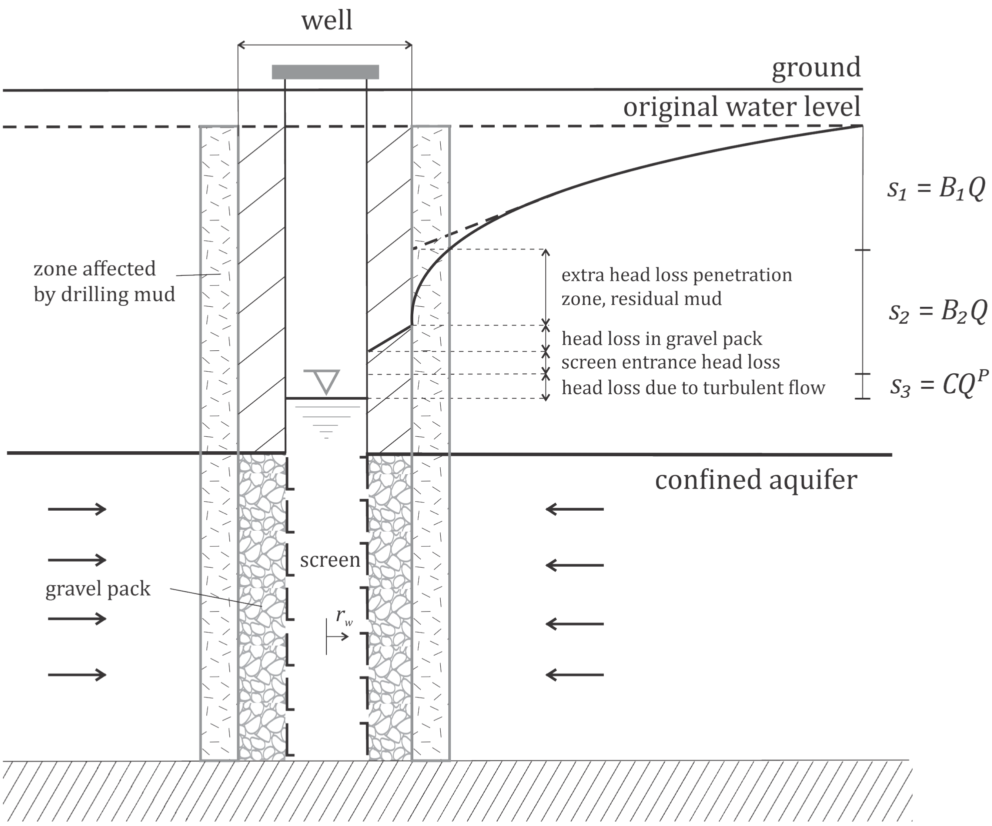



Fig. 1. Various components of head losses in a production well (modified from Kruseman and de Ridder, 1990).

Sl. 1. Različne komponente tlačnih izgub v črpalnem vodnjaku (prirejeno po Kruseman in de Ridder, 1990).

de Ridder, 1990). Therefore, we can determine $B$ ($B_1$+$B_2$) as aquifer circulation loss coefficient representing linear losses related as suggested, mainly to laminar flow nature and the drawdown is than (8) (Rorabaugh, 1953):

$$s = BQ + CQ^P \tag{8}$$

where $BQ$ and $CQ^P$ are drawdowns due to linear and nonlinear losses respectively. According to Lennox (1966), the value of $P$ is assumed to be in between 1.5 to 3.5, depending on the value of $Q$. Originaly Jacob (1947) suggested that the total drawdown in the production well could be expressed as the sum of drawdown due to laminar flow ($BQ$) and drawdown due to production well turbulence ($CQ^2$). This model was applied for the step-drawdown tests interpretation in this research. According to Jacob the drawdown in pumping well can be defined as (9):

$$s = BQ + CQ^2 \tag{9}$$

In literature, the ratio of the aquifer head loss to the total head losses is expressed as a well efficiency (10):

$$E_w = \left[\frac{B_1Q}{BQ + CQ^2}\right] \times 100\% \tag{10}$$

Values of $E_w \geq 70$ % or more is usually considered acceptable and indicate a properly designed and developed well (Kresic, 1997). The well efficiency can be expressed both with the results of a step–drawdown and aquifer test. The latter is needed in order to determine the value of $B_1$. In practice, only the drawdown measurements in a pumping well are usually available, therefore the value of $B_1$ cannot be determined. The substitution of $B$ and $C$ into equation (10.) would overestimate the well efficiency since $B > B_1$. Driscoll (1986) therefore introduced parameter $L_p$ representing laminar losses, which are interpreted as a ratio of the laminar head losses to the total head losses (11) (Kruseman and de Ridder, 1990):

$$L_p = \left[\frac{BQ}{BQ + CQ^2}\right] \times 100\% \tag{11}$$

In case of examined step-drawdown tests the values of $B_1$ and $B_2$ cannot be calculated, therefore the sum of linear well and aquifer losses is assumed as a parameter of linear head loss ($BQ$). Introducing the laminar loss ($L_p$) in order to evaluate the ratio between non-linear well loss and linear head loss, leads to assumption that linear well losses are also due to laminar flow. One could argue such simplification, but for the purpose of this research the conservative approach should satisfied the previous stated arguments.

Some researchers propose the comparison between wells based on range of $C$ value (Walton, 1962) or $C/B$ ratio (Bierschenk, 1963) in order to approximate well development indicating well deterioration and possible screen clogging. However, such comparison might work in case of large diameter wells, but it is not appropriate in our case remarking the uncertainties explained hereinafter. Mogg (1969) asserted that the magnitude of $C$ should not be used as an indicator of whether or not the well is properly designed or effectively developed because the correlation of field data shows that $C$ is inversely proportional to the product of the discharge rate and the specific capacity. In this paper we classify the well performance into three groups, according to $L_p$ value: good well performance ($L_p > 70$ %), medium well performance (30 % $< L_p \leq 70$ %) and poor well performance ($L_p \leq 30$ %).

The relationship between the drawdown and discharge can be expressed as the *specific capacity* of a well, $Q/s$, which describes the productivity of both the aquifer and the well. The specific capacity is not a constant but decreases as production continues. Several factors affect the specific capacity e.g. aquifer characteristics (hydraulic conductivity and storage coefficient), hydraulic barriers, technical performance of the well (e.g. penetration of well) and effective well screen perforation. The $Q/s$ ratio is useful also to compare pumping tests at different periods and allows predicting possible changes in well performance due to technical issues or variable hydraulic conditions in aquifers.

### Step-drawdown test performance

In step-drawdown tests groundwater is extracted in a number of consecutive time-intervals during which the pumping rate is constant but increases steadily with the number of time-intervals (Driscoll, 1986). By plotting $s/Q$ versus $Q$ and fitting the straight line thought the measurements points, the well coefficient $C$ is given by the slope of the line and the aquifer loss coefficient $B$ is equal to the intercept, considering $P = 2$ (Kruseman & de Ridder, 1990). The reliability of the derived value for $C$ increases with the number of steps, since more data points are available to derive the slope of the straight line in the $s/Q$ versus $Q$ plot. The number of pumping steps is determined on the basis of known production rate, aquifer characteristics and available time interval for test performance, including pre-pumping interval and groundwater recovery when the well is not producing. All pumping steps have to be of same duration, usually 30 – 120 min or till drawdown stabilization in order to provide the minimal storativity effect (Kruseman and de Ridder, 1994). The maximum pumping rate has to be determined according to maximum exploitation rate of the well, or better should fit maximum pump capacity. The Jacob (1947) graphical method idea is that the drawdowns measured at the end of individual steps should be steady. However, in reality, drawdown in a pumping well seldom stabilises. As a result, the quasi-steady drawdown measured at the end of each step is generally used in the analysis (Louwyck et al., 2009).

Table 1. Basic information about the performed step-drawdown tests.
Tabela 1. Osnovne informacije o izvedbi črpalnih preizkusov v korakih.

| Well num. | Aquifer[1] | WT[2] | Date | N[3] | Stab.[4] | Well num. | Aquifer[1] | WT[2] | Date | N[3] | Stab.[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | I | T | 22.02.2018 | 3 | yes | 16 | F | T | 28.08.2017 | 4 | yes |
| 2 | I | T | 14.12.2017 | 4 | no | 17 | F | T | 05.04.2017 | 3 | yes |
| 3 | F | T | 22.11.2017 | 4 | yes | 18 | F | T | 04.04.2017 | 3 | yes |
| 4 | F | T | 15.11.2017 | 4 | yes | 19 | F | T | 29.11.2017 | 3 | no |
| 5 | F | T | 30.01.2018 | 3 | yes | 20 | F | T | 28.11.2017 | 3 | no |
| 6 | F | T | 30.06.2017 | 3 | yes | 21 | F | M | 27.12.2017 | 3 | yes |
| 7 | F | T | 29.06.2017 | 3 | yes | 22 | I | M | 14.05.2016 | 3 | yes |
| 8 | F | T | 07.06.2017 | 3 | no | 23 | I | M | 13.05.2016 | 3 | yes |
| 9 | F | T | 29.06.2017 | 3 | yes | 24 | I | M | 07.05.2016 | 3 | yes |
| 10 | F | T | 15.11.2017 | 4 | yes | 25 | I | M | 20.04.2016 | 3 | yes |
| 11 | I | T | 05.12.2017 | 3 | no | 26 | I | M | 21.04.2016 | 3 | yes |
| 12 | I | T | 20.12.2017 | 3 | no | 27 | I | M | 25.04.2016 | 3 | yes |
| 13 | I | T | 19.12.2017 | 4 | no | 28 | I | M | 22.04.2016 | 3 | yes |
| 14 | I | T | 16.11.2017 | 3 | no | 29 | I | M | 03.05.2016 | 3 | yes |
| 15 | F | T | 06.07.2017 | 1 | yes | 30 | I | M | 26.04.2016 | 3 | yes |

[1]Aquifer type: I = intergranular, F = fractured
[2]WT (Water type): T = thermal, M = mineral
[3]Number of pumping steps
[4]Water level stabilization before pumping

### The Slovenian examples

Step-drawdown tests were performed in 30 wells in years 2016 (8 wells), 2017 (19 wells) and 2018 (3 wells). At some sites (users), several wells were tested (Fig. 2). In Slovenia, one third of tested wells exploit mineral water while the other two thirds exploit thermal water (Table 1). Half of tested wells produce water from intergranular aquifers (mostly sandy layers) and others from fractured aquifers (mostly dolomite). In general, three pumping steps were applied, while in six cases we were able to perform four pumping steps. In one case, the pumping rate was decreasing while the drawdown in the well progressed, therefore it was impossible to maintain the stable discharge during pumping. This case was not included in further analysis. All tested wells have been granted water concession and are active.

Age of tested wells at reference year 2017 is between 6-60 years (Table 2). Water temperature is up to 63 °C in exploitation wells for thermal water and up to 30 °C in exploitation wells for mineral water. Low to high mineralized water can be found in tested wells according to EC range of 391-14300 μS/cm. $CO_2$ level is highest in exploitation wells for mineral water in intergranular aquifers. Prevailing Ca-Mg-$HCO_3$ water type in exploitation wells for mineral and thermal water in fracture aquifers is related to prevailing dolomite recharge area. Na-Cl water type can be found only in one well in the coastal area. Various water types can be found in intergranular aquifers from Ca-Mg-$HCO_3$ to Na-Ca-$HCO_3$-Cl in wells exploiting mineral water and from Na-$HCO_3$ to Na-$HCO_3$-Cl in wells exploiting thermal water.

Table 2. Summary information on well ages and basic physico-chemical composition of water for four aquifer type categories.
Tabela 2. Povzetek informacij o starosti vrtin in osnovnih fizikalno-kemijskih značilnostih vode za štiri tipe vodonosnikov.

| Category | Well age (years) | T (°C) | EC (μS/cm) | $CO_2$(g) (mg/l) | Water type |
|---|---|---|---|---|---|
| FM | 6 | 12,5 | 400 | nd | Ca-Mg-$HCO_3$ |
| IM | 10-46 | 10-30 | 650-6450 | 176-2420 | Ca-Mg-$HCO_3$ to Na-Ca-$HCO_3$-Cl |
| FT | 7-49 | 21-40 | 391-14300 | 37-200 | Ca-Mg-$HCO_3$ to Na-Cl |
| IT | 12-60 | 55-63 | 600-6813 | 20-50 | Na-$HCO_3$ to Na-$HCO_3$-Cl |

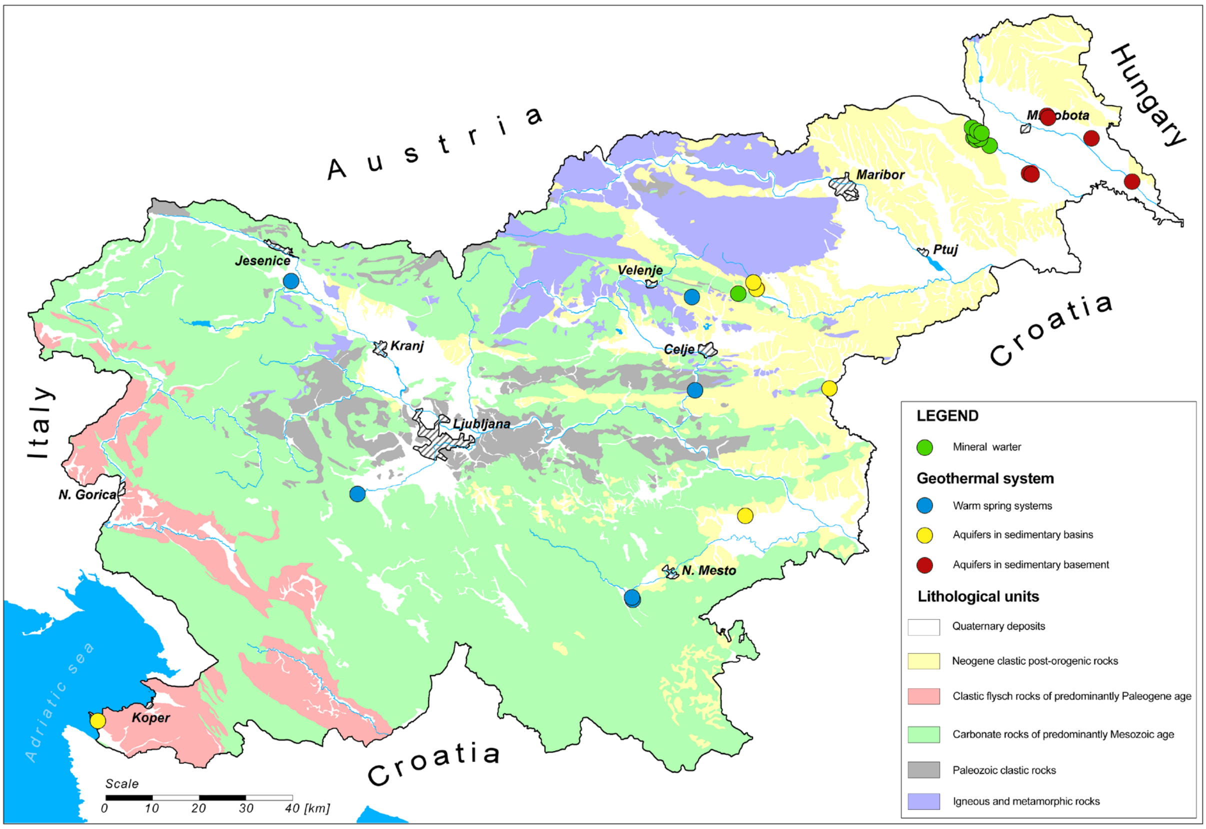



Fig. 2. Locations of tested wells.
Sl. 2. Lokacije testiranih vrtin.

All tests were performed taking into account the recommendation from the literature (e.g. Kruseman & De Ridder, 1990) as well as international standards (ISO 22282-4:2012). Nevertheless, there were several issues identified during step test performance, mainly due to technical issues or limits depending on each site. Most common issue was inappropriate installment of measurement probes and water meters. Eventually the situation improved or we used our own probes during tests performance. Second issue was the available time for test performance. Almost all wells are active and the water exploitation is constant. Therefore, the time available for test performance (discharge reduction) was short and in some cases the recovery time prior to pumping for the test was insufficient to achieve an equilibrium static head before pumping started. It was evaluated that the water level stabilization before pumping was achieved in 70 % of wells, while in other remaining wells the static head was at least very close to stabilization. During the step test performance, the stabilization level at each step was achieved only in 44 % of wells, even if the pumping step duration was in between 1.5 – 2 hours in 85 % of tests. That is a consequence of relative limited and slow water flow towards wells which is typical for investigated aquifers with a very low recharge rate. The pumping rate at each well was roughly determined preliminary, before step test performance. Still, in 37 % cases, the actual applied pumping rate was different to preliminary proposed, most commonly due to unknown technical characteristics of water pump prior to the tests.

## Results and discussion

### An example of a case study

To illustrate the applied analysis of step-drawdown test, an example of successfully performed pumping test in a well drilled in the intergranular aquifer is presented. The test was performed with four pumping rates: 6 l/s, 17.1 l/s, 22.3 l/s and 27.9 l/s. Each rate was maintained for 1.5 h (Fig. 3a). Measured drawdown versus elapsed time after pumping began was then plotted on semi-logarithmic graph (Fig. 3b). Each step was extrapolated with a straight line beyond the period of pumping in order to obtain the incre-

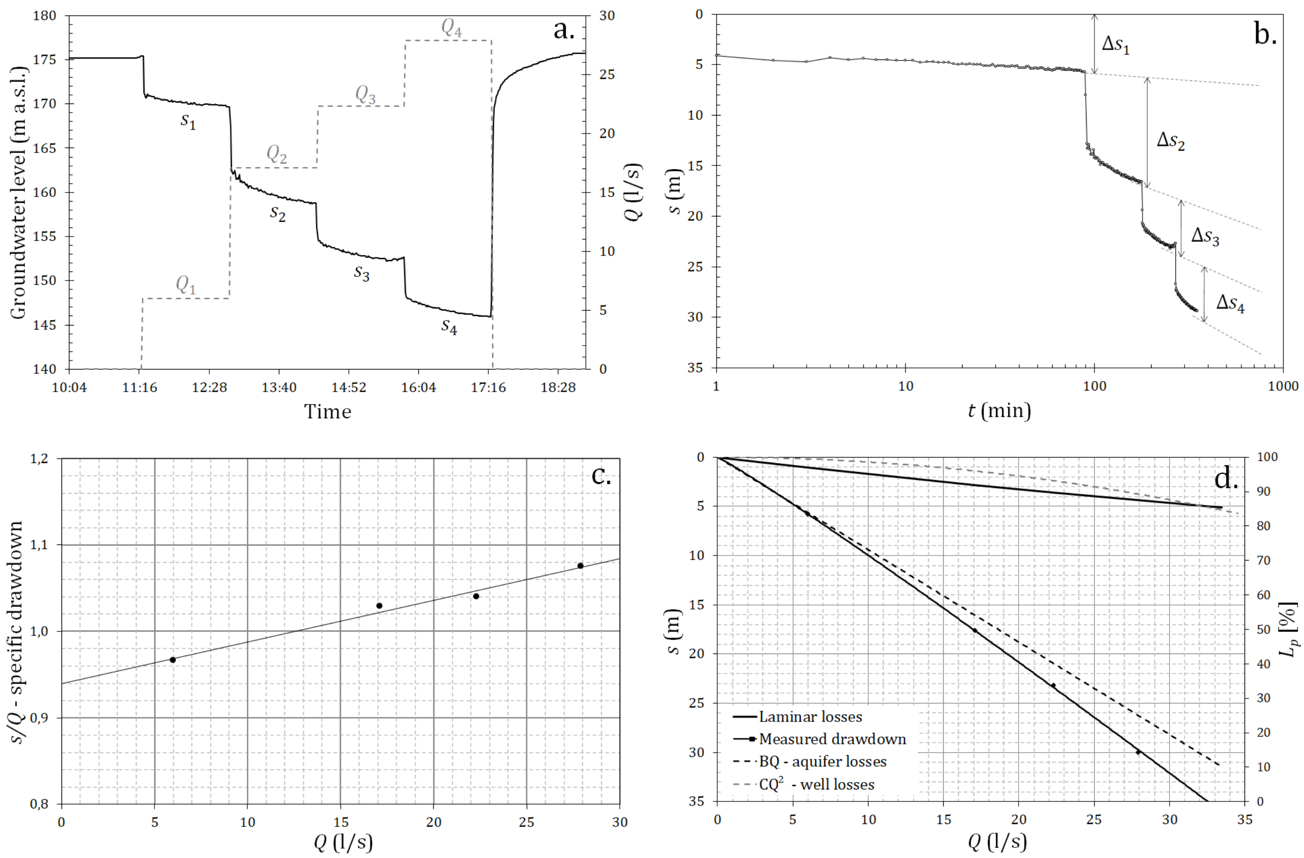



Fig. 3. Example of a step test performance: a.) field measurements of GWL and pumping rates, b.) drawdown versus time since pumping started, c.) specific drawdown versus pumping rate and d.) graphical interpretation of the step test analysis.

Sl. 3. Primer izvedbe črpalnega preizkusa v korakih: a.) terenske meritve gladine podzemne vode in črpane količine, b.) zniževanje v času od pričetka črpanja, c.) specifično zniževanje v odvisnosti od črpane količine in d.) grafična interpretacija analize črpalnega preizkusa v korakih.

mental drawdown caused by different pumping rates. Then $s/Q$ (specific drawdown) versus corresponding value of $Q$ was plotted on arithmetic graph (Fig. 3c). This approach is used to determine coefficient $B$ (linear losses) and $C$ (nonlinear losses) and was proposed by Hantush (1964) and Bierschenk (1963). Plotting the $s/Q$ values against the corresponding values of $Q$ gave a straight line with a specific slope representing the $C$ coefficient, while the coefficient $B$ represents the value at $Q$ = 0 l/s. The data falls on a straight line (Fig. 3c). The values of identified coefficients were determined as $B$ = 0.9397 s/m$^2$ in $C$ = 0.0048 m·s$^2$/l$^2$ in this case respectively. Using those coefficient values, we can write the drawdown approximate equation (12):

$$s / Q = 0.0048Q + 0.9397 \tag{12}$$

where

$$s = 0.0048Q^2 + 0.9397Q \tag{13}$$

hence this is a shape of Jacob equation and represents estimation of drawdown in the well within the time interval of 1.5 h.

Fig. 3d represents drawdown measurements, calculated linear losses ($BQ$), well losses ($CQ^2$) and portion of laminar losses for each pumping rate. In the example a drawdown of 30 m was observed at maximum discharge rate of $Q$ = 27.9 l/s. Applying the Jacob equation, the observed drawdown is a consequence of linear loss (aquifer and well loss), which theoretically is approx. $BQ$ = 26.22 m, and non-linear well loss, which is approx. $CQ^2$ = 3.74 m. At maximum pumping rate the well performance was determined as good, while the 87.5 % of measured aquifer at maximal pumping rate can be attributed to the aquifer loss. Also, the laminar losses decrease slowly.

The average exploitation rate of presented well at normal production is about 3 l/s during summer and 28 l/s during winter. High laminar losses mean that this pumping rate does not significantly affect well performance neither reaches the aquifer production capacity. Therefore, the winter exploitation rate of 28 l/s for the tested well does not exceed the well maximum capacity.

Still, each well reflects its own characteristics, therefore it is almost impossible in practice to consider all wells with the same conceptualization. It must be emphasized that step test can only help to determine production capacity and performance of the well and is not intended to determine sustainable production rates of the aquifer.

## Comprehensive summary analysis

### Well performance

The results of well performance analysis are available for 26 of total 30 tested wells (Table 2). Step-drawdown tests in wells 15, 18 and 21 have been subjected to technical issues, either due to inappropriate equipment installation or reduction of pump efficiency due to large drawdowns which resulted in unstable pumping rate. Figure 4 shows the distribution of well loss coefficient $C$ separately for thermal water wells in fractured and integranular aquifers and for mineral water wells. The values are ranging between 0.37 and 447 min$^2$/m$^5$ (conversion 1 min$^2$/m$^5$ = 0.0036 m·s$^2$/l$^2$). In the first decade $C$ < 1 min$^2$/m$^5$ there are 2 wells, 9 wells in $C$ = 1 – 10 min$^2$/m$^5$, 9 wells in $C$ = 10 – 100 min$^2$/m$^5$ and 7 wells in $C$ > 100 min$^2$/m$^5$. Some researchers propose the comparison between wells based on range of $C$ value in order to approximate well development indicating well deterioration and possible screen clogging (Walton, 1962). But well loss coefficient $C$ is empirically derived and therefore depending on several factors as for example effective open area of perforation. Each well was designed, constructed, and completed for specific reasons in different areas under varying hydrogeological conditions, so direct comparison among wells is not possible. For example, the wells exploiting mineral water would according to high $C$ value ($C$ = 10 – 100 min$^2$/m$^5$) indicate very poor well development, but still in same cases the laminar losses are high. Hence those mineral water wells are usually drilled with small diameter since the production rate is often lower than 5 l/s. As suggested by Mogg (1969) the low discharge rates in poor formations would show high values of $C$, which is often the case in mineral water wells.

Another parameter which might also affect the comparison between wells is the penetration factor (Bierschenk, 1963). The partial penetration increases the drawdown in a well because some of the water that enters the well must percolate upward or downward from the screen or perforations. Water percolating vertically to a well moves through a greater distance than if it had percolated horizontally and across planes of greater resistance (i.e. horizontal permeability is greater than vertical permeability). Therefore, using $C$ values for evaluation of wells status over time would only work in wells of similar technical properties. Consequently, in the presented case it would not be appropriate.

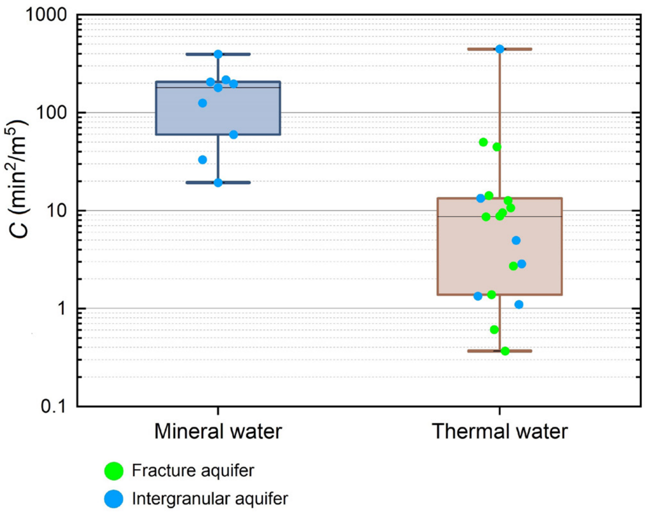
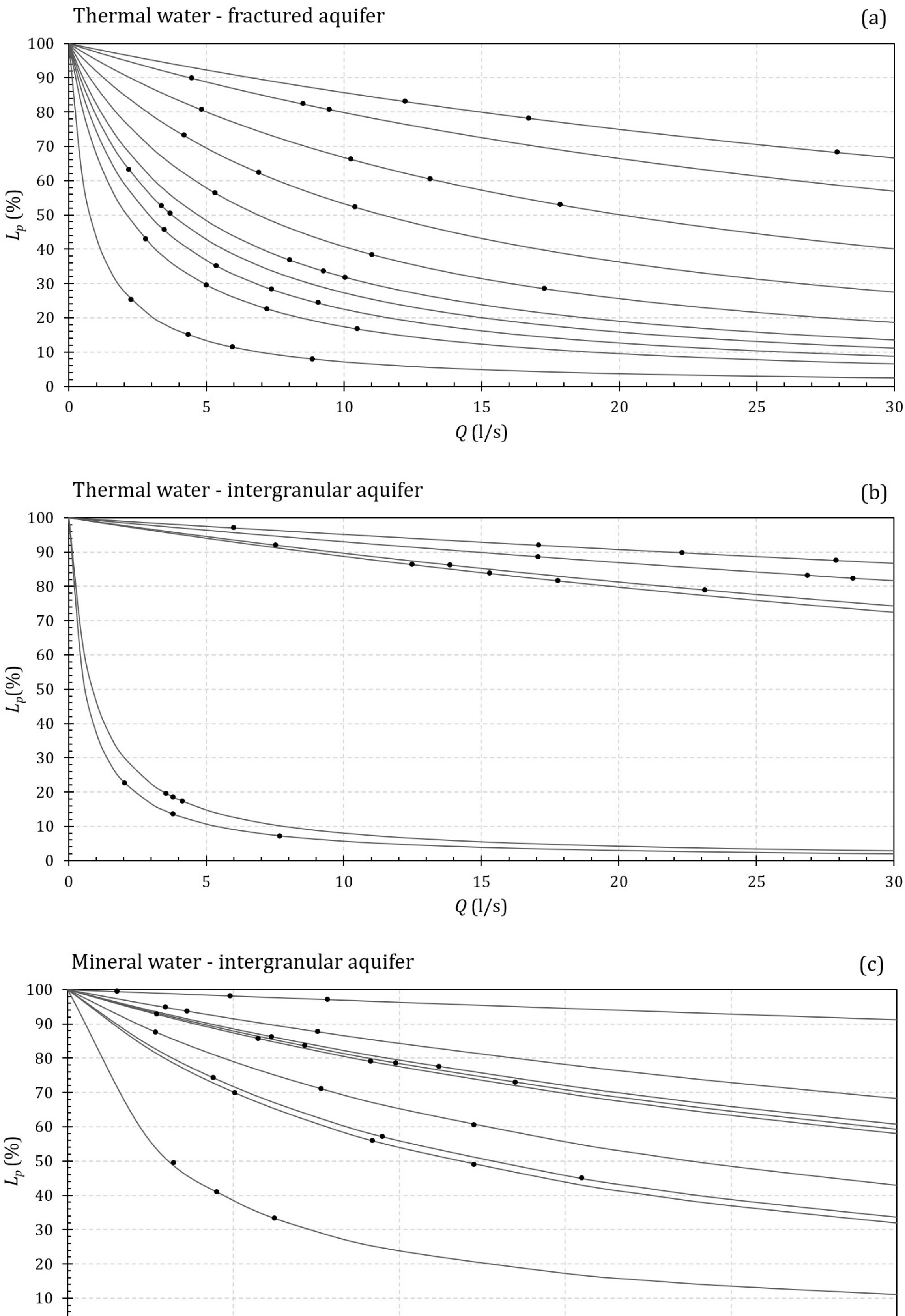



Fig. 4. Distribution of $C$ coefficient for different water and aquifer types.
Sl. 4. Porazdelitev koeficienta $C$ za različne tipe vod in vodonosnikov.

Graphical analysis led to production of curves representing the interpolation of laminar losses in individual wells (Fig. 5). Each figure includes curves for the wells exploiting thermal water, separately for fractured or intergranular aquifers and mineral water and each curve represents an individual pumping test. In some cases, extended extrapolation was used in order to compare results at the same scale. In general, they all show a decrease of laminar losses with increasing pumping rate. At the onset of turbulent flow, the specific capacity ($Q/s$) decreases proportionally to the increase of pumping rate and, at the same time, the laminar losses are reduced. Analysis of step drawdown tests has shown that simplified interpretations and comparison between the wells is not straightforward, but requires a detail knowledge about the system. Each well reflects specific characteristics and conditions in which the test was performed. Therefore, even a small change of hydraulic boundary condition (e.g. activation of additional fractures, hydraulic barriers, ...) significantly affects the test performance. Hydraulic characterisation of carbonate aquifers with fissured porosity is due to specific conditions, which are determined by pronounced heterogeneity and anisotropy, much more complex than the characterisation of aquifers with intergranular porosity. The dual porosity conceptualization based on the hydraulic exchange between different fractures dimensions is significantly affecting the well performance, resulting in significantly variable $Q/s$ ratio at each step.

The theoretical laminar losses were compared with maximum allowed production rates as determined in concession decrees (Table 1). Wells 9 and 20 suggest negative linear head loss coefficient ($B$) and therefore cannot be evaluated by calculating laminar losses. Detailed interpretation of calculated $B$ values were not taken into account, since it was impossible to separate the linear well losses and aquifer losses. The negative $B$ value which was calculated in two wells is most likely related to »breakthrough« pressure, which means that a certain pressure difference must be reached to develop a depression cone. Moreover it can also be assumed that negative $B$ value indicate significant permeability reduction at the wellbore (e.g. compaction of the material during drilling, clogging from drilling mud,...). It is also assumed that the negative $B$ values is related to significant time dependant aquifer characteristics. Those are especially important in fractured aquifers where the heterogeneous fractured media determines the hydraulic boundary conditions.

Laminar losses ($L_p$) in table 2 were calculated for maximum production rate as determined in concession decree ($Q_{max}$ CD). In case of 14 wells, the laminar losses are higher than 50 %, which means that linear head losses (aquifer and well) are still more important than nonlinear well losses. The detailed results are presented in Table 1. Based on step-drawdown test results it was possible to evaluate either a maximum production rate ($Q_{max}$) should change (increase, decrease) or stay equal prior to $Q_{max}$ CD. From the total of 25 wells for which it was possible to calculate laminar losses, 11 can be addressed with good well performance. In all this wells, except one, the $Q_{max}$ CD can be increased and decree corrected. This is because the well losses represent a relatively small portion in the measured drawdown even after years of thermal water production. Medium well performance was identified in case of 7 wells. Also, in these wells, except one, the $Q_{max}$ CD can be increased and decree corrected. Five of those wells are producing mineral water with relatively low production rate. Therefore, the increased maximum production rate will not affect the aquifer capacity as allowed annual production quantity will not be changed in decrees. The other two wells are drilled in fractured aquifer where calculation of laminar losses can be uncertain. In 7 wells where their performance was evaluated as poor, the $Q_{max}$ CD not improved but on the contrary, in 3 wells the $Q_{max}$ CD should be decrease.




*Black points represent tested pumping rates.

Fig. 5. Laminar losses ($L_p$) in investigated wells according to water and aquifer type (a. thermal water – intergranular aquifer, b. thermal water – fractured aquifer and c. mineral water – intergranular aquifer).

Sl. 5. Laminarne izgube v preiskovanih vodnjakih glede na tip vode in vodonosnika (a. termalna voda – medzrnski vodonosnik, b. termalna voda – razpoklinski vodonosnik in c. mineralna voda – medzrnski vodonosnik).

Table 3. Results of step-drawdown test analysis for 30 thermal and mineral water wells in Slovenia.
Tabela 3. Rezultati črpalnih preizkusov v korakih za 30 testiranih termalnih vrtin in vrtin z mineralno vodo v Sloveniji.

| Well number | $Q_1$ | $Q_2$ | $Q_3$ | $Q_4$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $s_1$ | $s_2$ | $s_3$ | $s_4$ | $C$ | $B$ | $Q_{max}$ CD | $Q_{max}$ | $Lp$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | l/s | | | | min | | | | m | | | | $m \cdot s^2/l^2$ | m·s/l | l/s | l/s | % |
| 1 | 3.6 | 3.8 | 4.1 | / | 109 | 115 | 116 | / | 24.8 | 29.1 | 33.0 | / | 1.609 | 1.388 | 7 | 4.0 | 11.0 |
| 2 | 10.6 | 12.5 | 15.3 | 17.8 | 96 | 95 | 95 | 91.0 | 22.0 | 20.5 | 25.3 | 30.9 | 0.018 | 1.405 | 12 | 21.0 | 86.8 |
| 3 | 4.8 | 10.3 | 13.1 | 17.9 | 118 | 130 | 110 | 140.0 | 3.8 | 9.5 | 14.5 | 21.1 | 0.032 | 0.635 | 4.5 | 19.0 | 81.7 |
| 4 | 3.5 | 5.4 | 7.4 | 9.1 | 125 | 130 | 105 | 125.0 | 3.8 | 6.6 | 12.1 | 17.8 | 0.161 | 0.469 | 2 | 9.3 | 59.3 |
| 5 | 2.2 | 3.4 | 3.7 | / | 95 | 95 | 100 | / | 0.4 | 0.8 | 0.9 | / | 0.034 | 0.128 | 15 | 5.5 | 20.0 |
| 6 | 5.3 | 11.0 | 17.3 | / | 120 | 120 | 122 | / | 0.2 | 0.4 | 0.9 | / | 0.002 | 0.015 | 15.8 | 17.3 | 30.3 |
| 7 | 4.5 | 8.5 | 9.5 | / | 134 | 138 | 138 | / | 0.3 | 0.6 | 0.6 | / | 0.001 | 0.053 | 7 | 9.5 | 85.0 |
| 8 | 12.2 | 16.7 | 27.9 | / | 202 | 204 | 202 | / | 4.4 | 6.4 | 12.3 | / | 0.005 | 0.299 | 15 | 28.0 | 80.0 |
| 9 | 4.4 | 7.0 | 10.3 | / | 130 | 134 | 202 | / | 0.7 | 2.3 | 4.4 | / | 0.045 | −0.022 | 6.7 | 11.0 | / |
| 10 | 2.3 | 4.3 | 6.0 | 8.9 | 21 | 19 | 20 | 20.0 | 0.3 | 1.2 | 2.3 | 4.2 | 0.051 | 0.039 | 10 | 10.0 | 7.1 |
| 11 | 2.0 | 3.8 | 7.7 | / | 28 | 30 | 30 | / | 0.2 | 1.0 | 3.0 | / | 0.048 | 0.028 | 8 | 8.0 | 6.9 |
| 12 | 17.1 | 26.9 | 28.5 | / | 90 | 90 | 91 | / | 10.2 | 15.8 | 19.2 | / | 0.004 | 0.524 | 14.9 | 28.0 | 89.9 |
| 13 | 6.0 | 17.1 | 22.3 | 27.9 | 90 | 90 | 90 | 90.0 | 5.8 | 17.6 | 23.2 | 30.0 | 0.005 | 0.940 | 9.5 | 28.0 | 95.4 |
| 14 | 7.5 | 13.9 | 23.1 | / | 124 | 120 | 121 | / | 7.0 | 15.1 | 25.5 | / | 0.010 | 0.888 | 6 | 28.0 | 93.5 |
| 15 | 0.2 | / | / | / | 2901 | / | / | / | 133.0 | / | / | / | / | / | 0.79 | 0.4 | / |
| 16 | 2.8 | 5.0 | 7.2 | 10.5 | 125 | 120 | 120 | 120.0 | 0.5 | 1.4 | 3.0 | 4.7 | 0.038 | 0.081 | 11.1 | 11.1 | 15.9 |
| 17 | 4.2 | 6.9 | 10.4 | / | 120 | 120 | 120 | / | 2.0 | 4.0 | 7.0 | / | 0.031 | 0.355 | 28 | 28.0 | 29.0 |
| 18 | 4.5 | 6.3 | 7.3 | / | 120 | 120 | 120 | / | 5.0 | 7.0 | 3.0 | / | / | / | 11 | / | / |
| 19 | 8.0 | 9.3 | 10.0 | / | 30 | 30 | 30 | / | 1.0 | 1.3 | 1.5 | / | 0.010 | 0.046 | 8.5 | 8.5 | 29.3 |
| 20 | 2.2 | 3.6 | 6.0 | / | 17 | 23 | 24 | / | 0.4 | 1.3 | 5.0 | / | 0.180 | −0.253 | 11.3 | 5.0 | / |
| 21 | 0.3 | 0.5 | 0.8 | / | 120 | 138 | 102 | / | 40.0 | 68.0 | 113.0 | / | / | / | 2 | 0.8 | / |
| 22 | 0.6 | 0.7 | 1.5 | / | 91 | 197 | 200 | / | 4.0 | 5.9 | 11.9 | / | 0.648 | 6.976 | 1.1 | 1.6 | 90.7 |
| 23 | 0.3 | 1.0 | 1.6 | / | 139 | 185 | 182 | / | 1.1 | 3.4 | 6.0 | / | 0.069 | 3.602 | 1.39 | 3.5 | 97.4 |
| 24 | 0.5 | 1.5 | 2.5 | / | 90 | 231 | 188 | / | 1.8 | 6.2 | 11.9 | / | 0.779 | 2.926 | 2.35 | 2.6 | 61.5 |
| 25 | 0.6 | 0.9 | 1.3 | / | 183 | 181 | 185 | / | 1.1 | 2.0 | 3.3 | / | 1.424 | 0.891 | 1 | 1.4 | 38.5 |
| 26 | 0.9 | 1.9 | 3.1 | / | 179 | 178 | 181 | / | 0.4 | 1.0 | 2.1 | / | 0.119 | 0.302 | 3 | 4.8 | 45.8 |
| 27 | 0.5 | 1.2 | 1.8 | / | 85 | 188 | 321 | / | 1.7 | 4.7 | 6.9 | / | 0.452 | 3.127 | 1.42 | 2.0 | 83.0 |
| 28 | 1.2 | 2.2 | 5.3 | / | 166 | 188 | 981 | / | 2.3 | 4.9 | 14.8 | / | 0.215 | 1.661 | 5 | 5.0 | 60.7 |
| 29 | 1.4 | 2.0 | 2.7 | / | 191 | 181 | 181 | / | 8.6 | 13.6 | 18.7 | / | 0.709 | 5.162 | 2.4 | 2.4 | 75.2 |
| 30 | 1.0 | 1.8 | 2.5 | / | 183 | 179 | 247 | / | 2.6 | 5.5 | 8.9 | / | 1.609 | 1.388 | 2.36 | 2.5 | 49.8 |

## Conclusion

In the present study, an attempt has been made to evaluate and compare the well performance using Jacob empirical method for calculation of well losses and aquifer losses. This parameter was recognized as very useful in order to quantify technical characteristics of production mineral and thermal water wells also referred to well efficiency. On the contrary, well loss coefficient magnitude was recognized as a very inappropriate indicator whether the well is properly designed or effectively developed. The presented approximate method of step-drawdown test interpretation calculates only the nonlinear component of well loss, while the linear component, which is generated due to partial penetration, skin effect or hydrogeological boundary effect, is included within the linear head loss.

Most of the tests (23 of 30) were carried out in three steps, averaging up to 1.5 hour for each. The drawdown stabilization during pumping was reached in approximately 70 % of wells. The main problems for the successful implementation were: insufficient observation equipment, a non-optimal system for regulating the pumping discharge rate, rare observation wells and a constant need for water production. The latter prevented either the establishment of constant pumping rate or complete suspension of production for several hours. There are many potential improvements in test implementation, but they are to a certain extent related to investments in the technology system for the use and control of the use of groundwater by the concessionaires.

Although a lot of investigated wells are a few decades old, surprisingly the calculated laminar losses were higher than 70 % in 44 % of these. Moreover, the analysis showed that for a large number of wells (at least 7), their performance is relatively poor, which means that the nonlinear losses in the well are significantly higher than the linear losses in the aquifer. It is expected that such situation may be attributed to the inappropriate technical condition of the well in some places (e.g. well deterioration). A special consideration was given to 28 % of wells where the calculated laminar losses were between 30 and 70 %. In such cases it is very difficult to obtain an appropriate conclusion, since in most cases a technically appropriate step drawdown test was performed for the first time. Therefore, it was impossible to compare the acquired data with previous tests and consequently, impossible to evaluate time-dependant changes in well performance.

The results indicate possible changes in the technical condition of some wells. However this will be verified only when at least two comparable step-drawdown tests will be performed in each well. In order to timely implement measures for preventing further deterioration, it is necessary to constantly monitor the well performance. Further investigation will include also constant-rate pumping test in order to determine hydraulic properties of the aquifer along with the consideration of the total well losses and consequently the significance of the linear well loss component.

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## Nomenclature

| Symbol | Parameter | Unit |
|---|---|---|
| $s$ | Drawdown | m |
| $s_{1,2,3,4}$ | Drawdown for each step respectively | m |
| $s_w$ | Well loss drawdown | m |
| $s(t)$ | Measured drawdown | m |
| $s(r_w,t)$ | Drawdown with no well loss | m |
| $t$ | Time | min |
| $t_{1,2,3,4}$ | Duration of each step respectively | min |
| $r_w$ | Well radious | m |
| $T$ | Transmisivity | $m^2/s$ |
| $Q$ | Discharge (pumping rate) | l/s |
| $Q_{1,2,3,4}$ | Pumping rate for each step respectively | l/s |
| $W(u)$ | Theis well function | / |
| $S$ | Storage coefficient | / |
| $B_1$ | Linear aquifer loss coefficient | m·s/l |
| $B_2$ | Linear well loss coefficient | m·s/l |
| $P$ | Exponent of the well discharge | / |
| $B$ | Aquifer circulation loss coefficient | m·s/l |
| $C$ | Non-linear well loss coefficient | $m{\cdot}s^2/l^2$ |
| $E_w$ | well efficiency | % |
| $L_p$ | Laminar losses | % |
| $Q_{max}$ $CD$ | Maximum production rate determined in concession decree | l/s |
| $Q_{max}$ | Maximum production rate suggested by step-drawdown test | l/s |

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