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Automatic field measurement of groundwater discharges in a tunnel

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Abstract.
The paper describes a complex project of flow rate measurement applied for groundwater discharge into a tunnel, for both individual seepage points and the collection channel totalizing the flow. Various standard methods are used according to a large range of flow rate magnitudes (tipping bucket, danaid, V-shaped weir) with partial improvements and technical adaptations. Data collection is provided by individual measurement units with ethernet interface sending data to a database server through the internet. Experience of 10 years with several upgrades of either individual measurement or the electronic collection and transmission system is summarized.

1 Introduction

Flow rate measurement in hydrology and hydrogeology is one of the basic field research procedures [1]. Open-channel flow in streams is well established, including automation and data transmission, typically via the GSM network [2]. On the other hand, for the automated measurement of water discharge from the rock through the tunnel wall it is not routinely applied. For groundwater flow studies, the tunnel inflow spatial and temporal variations can be useful as extended information [3] compared to common field methods of borehole/well pressure tests [4], borehole water levels, and surface springs flow rates. Collected data from this study are e.g. used as an input to numerical models [5], [6].

The presented study is a part of projects related to geological disposal of the spent nuclear fuel and to the geothermal energy. In both cases, the detailed understanding of groundwater flow and the related physical processes (thermal, mechanical) in heterogeneous rock is important.

First part of the paper describes technical features of the measurement methods, automation, and data transmission. Then we present our experience from over 10 years long continuous measurement in order to review the applicability of various methods or how the data are influenced by the selected measurement method or by the complex groundwater phenomenon itself [7].

1.1 Bedřichov site

The measurement has run in the water supply tunnel in Jizera mountains, Czech Republic. The tunnel connects Josefův Důl reservoir with the water treatment plant in Bedřichov. It is about 2600 m long, with the height difference of 40 m. Pipe for the supply of raw water from the reservoir to the treatment plant leads through the tunnel. A detailed description of the site geology is provided in the report of Klomínský et al. [8].

Various phenomena are measured within the whole project: water inflow rates, pH, electric conductivity, natural tracer concentration, temperature, rock fracture displacements, seismicity etc., some in a cooperation with other research teams and institutions.

Particularly, the long time monitoring of groundwater discharging into the tunnel has been held in numerous observation points (see Fig. 1). It is based on the choice of basic observation points[1] Vn from the work [8], which were further supplemented with newly labelled observation points[2] Wx.

1.2 Character of the inflow

The in-situ measurement deals with flow rates at the numerous seepage sites with different character (from dropping through flowing individual seepages to the collecting channel flow representing the total tunnel inflow) and also with the large range of flow rate magnitude (from microlitres to litres per second):

1. Discharge points from the walls or ceiling of the tunnel. Depending on the flow rate magnitudes, they can be divided into:

- dripping (V1–V3; see Fig. 5),
- flowing (V4–V7, W142–W2313; see Fig. 5 or Fig. 7).

Depending on their rate variability, they can be divided into:

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[1] $n = 1 - 8, 10$
[2] x [m] is the position in the tunnel

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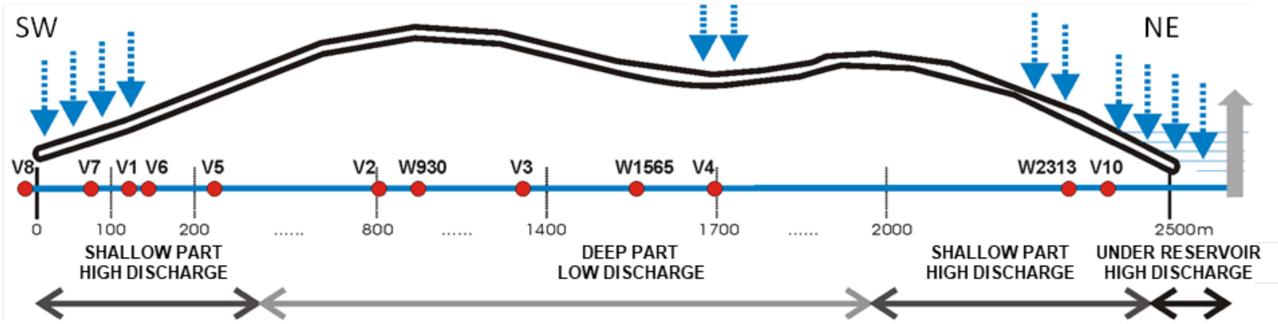

Fig. 1. Basic diagram of Bedřichov tunnel with the positions of selected discharge points and representation of the overburden.

Fig. 2. Water level measurement in the channel. On the left: ultrasonic probe (in the observation point V8). In the middle: a cylinder with the load string (H104). On the right: the pressure probe (H248).

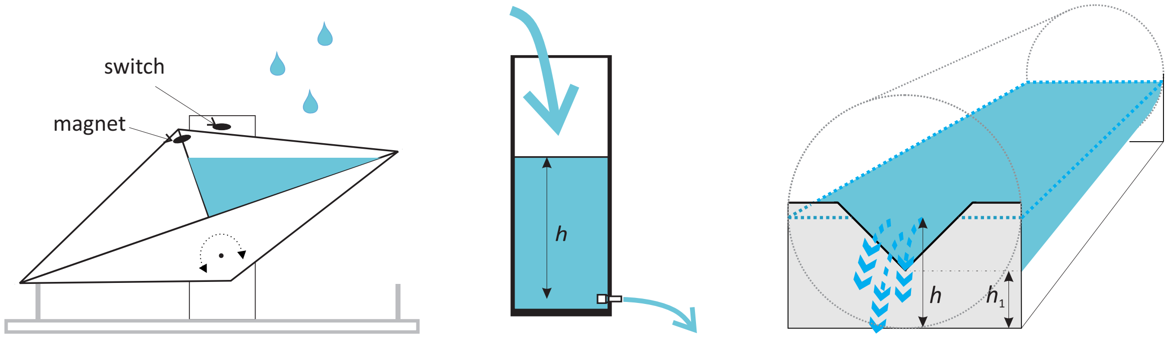

Fig. 3. From left to right: tipping bucket, danaide with one outlet, V-shaped weir; h is the actually measured quantity.

- discharge points in the deep part of the massif; with low variability (V2–V4, W930, W1565),
- discharge points in the shallow part; with large variability (V1, V6, V7),
- discharge points on the borderland between deep and shallow parts; with medium variability (V5, W2210, W2313).

2. Total discharge into the tunnel

Collecting channel at the bottom of the tunnel captures all discharges into the tunnel. By subtracting the flow values from two points in the channel, the total discharge in a given section of the tunnel can be obtained. The observation points[3] in the channel are labelled as Hx (Fig. 2).

[3] x [m] is the position in the tunnel

2 Groundwater discharge measurement

2.1 Methods of flow rate measurement

Various methods, reflecting the character and magnitude of inflow, are used (see Fig. 3):

- Tipping buckets: by filling the buckets with a known volume V and tipping them by its weight, a signal is induced by a reed switch and a magnet. They can record either (a) each tipping time t_i of the bucket (this regime has been actually used by us); the flow rate is $Q(t_i) = \frac{V}{t_i - t_{i-1}}$ or (b) the number of times n the bucket is tipped over a specified time Δt; the flow rate is then $Q = \frac{nV}{\Delta t}$. Differences are discussed in paragraph 4.1.
- Danaids: measuring vessels (cylinders) with one or more outflow orifices (with known sectional area S). They record the water level h in the vessel. The flow rate is then computed as $Q = \mu S\sqrt{2gh}$, where μ is the leaving coefficient of the orifice (0.9 for our case).
- Measuring cylinders[4]: they record increasing water level h in the cylinder; after the cylinder is filled, it is emptied and the whole process periodically repeats. With known sectional area S, the flow rate is $Q = \frac{S\Delta h}{\Delta t}$, where Δh is the level difference over the time inverval Δt.
- V-shaped weir: the flow rate is calculated from the height level $\hat{h} = h - h_1$ in the channel above the measured profile. For the profiles with 90° cut and $\hat{h} > 20$ cm, the flow rate can be computed as $Q = 1.343\ \hat{h}^{2.47}$.

Some of the methods have been modified by authors [10]. We present our experience of the use of each particular method. The examples of installations are shown in Fig. 2 and Fig. 5.

2.2 Water level measurement

The water level in the channel or in the vessel can be measured by various methods (for schemes, see Fig. 4; installations in Fig. 2):

- pressure probes compensated by atmospheric pressure or relative pressure; water level h can be then obtained from $h = \frac{p_{meas} - p_{atm}}{\varrho g}$, or $h = \frac{p_{meas}}{\varrho g}$, respectively,
- ultrasonic level sensor; $h = d - h_s$, where h_s is the vertical position of the sensor and d is the measured distance from the sensor to the water surface evaluated internally by the device from the reflected pulse travel time,
- load strings by a partially submerged weight; the load is measured by the resonance frequency of the loaded string (the excitation and electrical signal processing is a built-in operation of the device); then $\Delta h = (R_0 - R_1)G$, where R_0 is the initial value, R_1 is the actual value and G is the unique parameter for every device.

Methods differ both in their accuracy and in their installation (e.g. spatial) demands. This is in more details discussed in paragraph 4.3.

[4]original construction [9] patented by the Czech Geological Survey

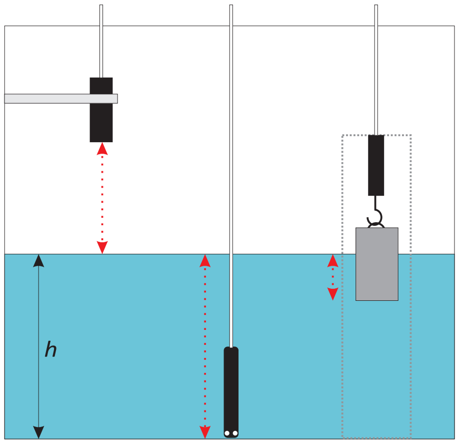

Fig. 4. Water level measurement. From left: ultrasonic probe, pressure probe, load string.

Fig. 5. Methods of the water discharge measurement. On the left: tipping bucket (observation point V2). In the middle: danaide (V7). On the right: measuring cylinder (W930).

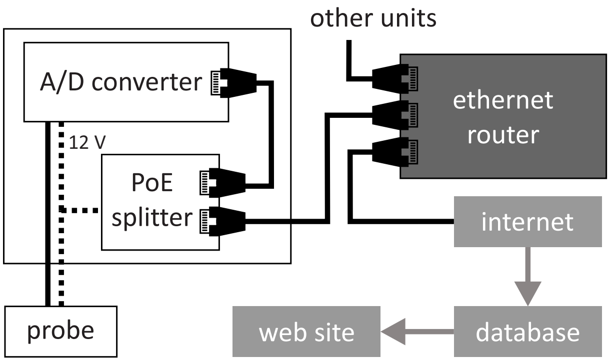

Fig. 6. Configuration of electric and data collection network, with an example of one measuring point.

3 Automatic data collection

During time, the measurement in a large part of the observation points was automatized, in particular in the 0-930 m chainage positions with electric and data network, while in the remaining part, loggers with internal memories and regular manual data download are used.

The first generation of the measurement and collection, established in 2010, is presented in [11]. It used the RS485 bus, own development of electronic modules, and GSM connection to the internet at the tunnel entrance.

The second generation is based on the ethernet network and commercial measuring units. At a particular discharge location, the system consists of (Fig. 6): sensor (depending on the method) + electrical connection (A/D converter or pulse counter) + ethernet connection. The data are stored in a database (kept since the first generation system) with public presentation at web page http://bedrichov2.tul.cz/ (results of [12], in trial mode; an example of visualised data is shown in Fig. 14).

The measurement methods are based on water level measurement (cylinders, weirs) or discrete pulse generation by tipping buckets. The data collection of an analog measurement is realized with the AD4ETH unit [13] with A/D converter from 4-20mA (= output of pressure LMP307i [14] or ultrasonic S18UAI [15] level sensors) sending HTTP GET requests regularly to web server with running PHP script which enters data to a PostgreSQL database. Longer interval of 10 minutes is used for cylinders with steady level and higher range and shorter interval of 1 minute is used for weirs to cut-off noise by averaging (see paragraph 4.1). The unit provides programmable linear conversion from the current range to the level value (mm).

The pulse counting is realized with Papago TH2DIDO [16], also with integrated ethernet interface and HTTP GET communication, sending data asynchronously, i.e. the counter value and time stamp from the device real-time clock, after each pulse. This avoids any loss of accuracy by sampling errors. Conversion from raw data (level in mm, counter) to flow rate units is implemented in the database through a trigger function.

Fig. 7. Complete equipment of the automatic measurement. Up: V6 discharge with probes. In the middle: cables leading from probes directly or trough Greisinger [17] transmitters into the water resistant box. Bottom: the box containing the PoE splitter, the A/D converter for general quantities and the Papouch A/D converter (here with its own PoE and the temperature sensor).

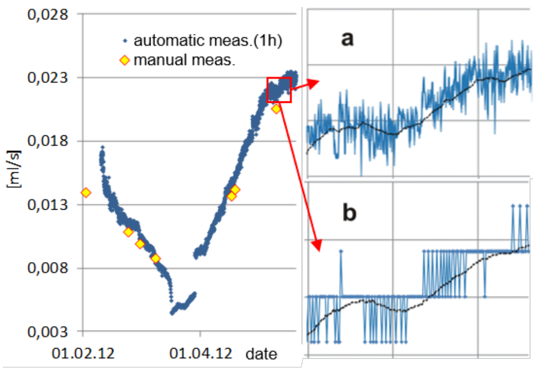

Fig. 8. Dripping seepage V2 – discharge level progression with detailed part of the course for two different record regimes of the tipping bucket (a – every tipping time; b – number of tips per 1 h). Daily floating averages (black lines) are rather similar.

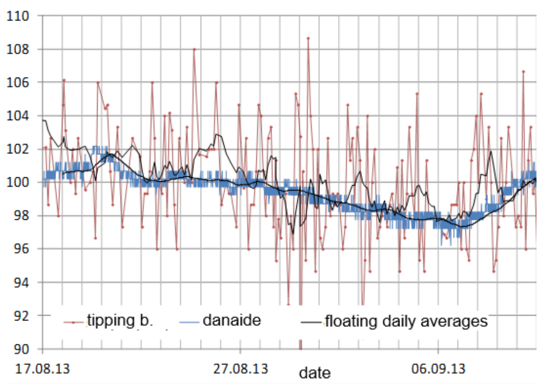

Fig. 9. V6 discharge variance [%] (rel. to time period average). Comparison between tipping bucket and danaide.

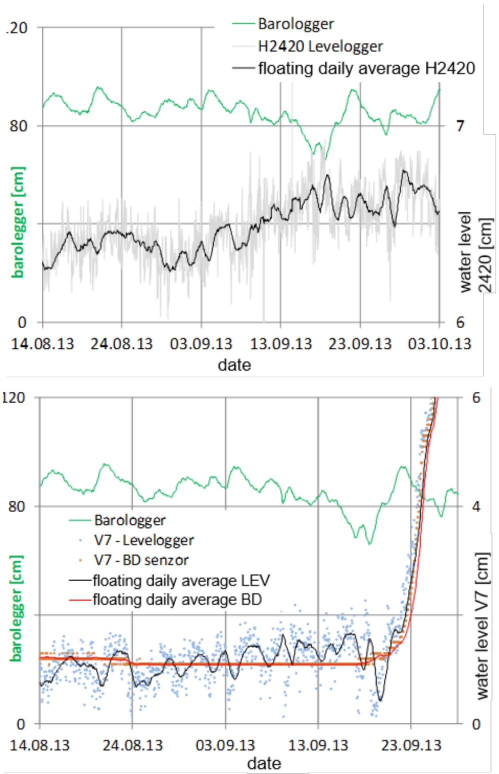

Fig. 10. Up: parallel courses of the atmospheric pressure and the automatically compensated water level in H248. The "overcompensation" is distinctive. Bottom: the same period recorded for V7 in comparison with relative pressure probe record (red line).

4 Our experience from the measurement

In the following paragraphs, we present some comments on the data post-processing, based on our experience from a long time in-situ measurement.

4.1 Data post-processing

The raw data, obtained by the measurement, include some noise or fluctuations, which have to be distinguished and post-processed. These fluctuation can be from various origins:

- Data influenced by the measurement method

  Typical example is the data from the tipping bucket (see Fig. 8). Whether we record time of each tip (case **a** on the Fig. 8) or their sum over a particular time period (case **b** Fig. 8), the flowing averaging is needed to obtain the well arranged graph. The case B provide more smooth curve, while the case A can catch the short time discharge fluctuations.

  Measuring vessels or danaids provides more smooth data than tipping buckets, given by their character. The smoothness relies purely on measurement frequency (we don't reflect the qualities of probes here). An illustrative example for the V6 discharge is shown in the Fig. 9.

- Data influenced by the measurement equipment

  This case is typical for the various methods of the water level measurement. The values from probes recording the relative pressure are almost ready to use without averaging (see red line in Fig. 10 bottom). In comparison, data from Levelogger probes, which need compensation to the atmospheric pressure, are relatively strongly influenced directly by this compensation. Natural atmospheric pressure fluctuation are qualitatively transposed (with opposite sign) to the water level data - something, which we can call overcompensation (see Fig. 10; the projected fluctuation are in a bold contrast with almost constant water level recorded by the LMP307i probe). The compensated data (after averaging) are suitable rather for long-term trends.

  There are usually different claims on the measurement sensitivity in time ranges of different lengths, which can be illustrated with the data from the measuring vessel: see Fig. 11 (the upper part for the period of several month and the bottom part for the period of years). For short time fluctuation, we have to record the actual water level; for long time trends, it is sufficient to record the filling-times.

  The main disadvantage of ultrasonic probes is that they record the noise caused by the water level surging (see Fig. 13). By contrast, in the string load measurement, the weight momentum compensates instant oscillations of the water level.

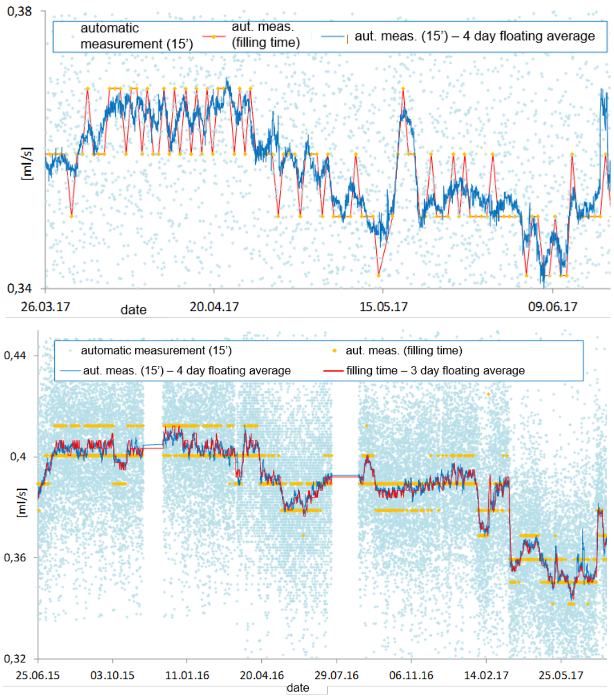

Fig. 11. Discharge level at W930. A comparison between continuous water level measuring (blue dots) and filling time recording (yellow dots with red line). Up: 3-month period. Bottom: 2-year period.

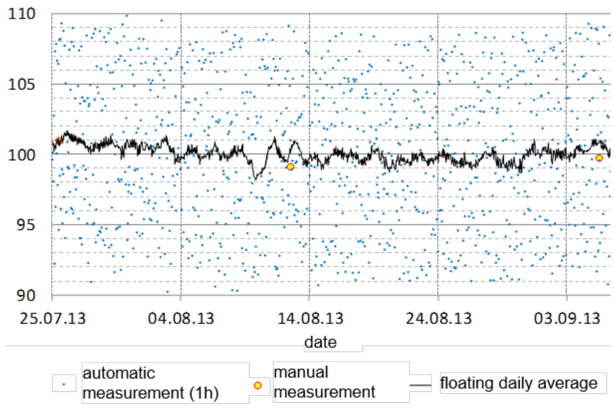

Fig. 12. V4 discharge variance (rel. to time period average %). Daily floating average embodies distinct fluctuation, caused by the atmospheric pressure compensation.

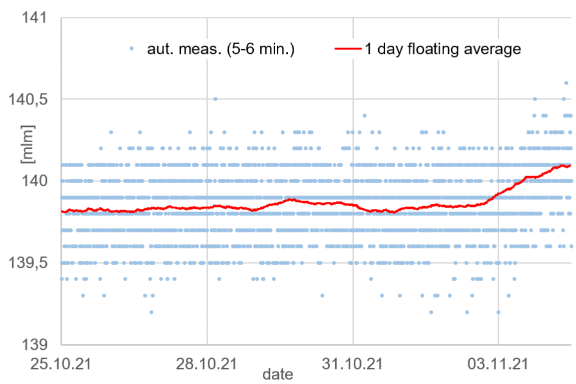

Fig. 13. H248 water level variance (ultrasound probe).

- Data influenced by the discharge itself

  Next to types of fluctuations caused by the measurement, mentioned above, the variability of the data can be caused by the momentary fluctuations of the discharge itself (which can even easily comprehend those measurement-caused fluctuations). This is characteristic for the discharge V4; momentary fluctuations, caused by the periodic aeration of the pipe, are fairly observable (with the variable period in low tens of seconds). On the other hand, the long-time flow rate is very stable.

  The Fig. 12 represents a 2-week record. While the data (recorded with 15 min. period) shows the variation about ±10% from the 2-week average, the real discharge level variation is about ±1% (documented by the manual measurement).

4.2 Measuring equipment efficiency

- Tipping buckets:

  They have been proven and suitable for dripping discharge points. In the case of flowing discharge points, their possibilities are limited: the shuttle mechanism becomes worn when using a tipping bucket with a small volume (in relation to the rate of the measured flow); tipping buckets with a larger volume are not sensitive to changes in the flow rate.

- Danaids:

  They have been proven for a wide range of rates of flowing discharge points, with a suitably chosen hole size and working height of the water level they are sensitive to changes in flow rates.

- Measuring cylinders:

  Their application field covers the borderland between tipping buckets and danaids. They are suitable for flowing or dripping discharge points with a stable or slowly changing flow rates. Sensitivity to changes in the flow rate depends on the frequency of data recording. For long-term trends in the yield of stable discharge points, records of cylinder fill times are sufficient.

- V-shaped weir:

  The used profile is not very sensitive to changes in flow rate, and even a slight change in the water level (even in the case of a ripple) is recorded in the fluctuation data. There is a need of the water level measurement accuracy better then millimeters, which is hard to achieve for some measuring principles (see next paragraph 4.3).

4.3 Measurement accuracy

The accuracy comparison of particular methods of water level measurement is presented in Table 1.

Ultrasonic probes have high relative accuracy. Moreover, they are not in the contact with water, which can avoid an origin of sediments or coagulation and prolong their working life.

Pressure probe has less accuracy in comparison with remaining measuring principles. Coagulation origin can

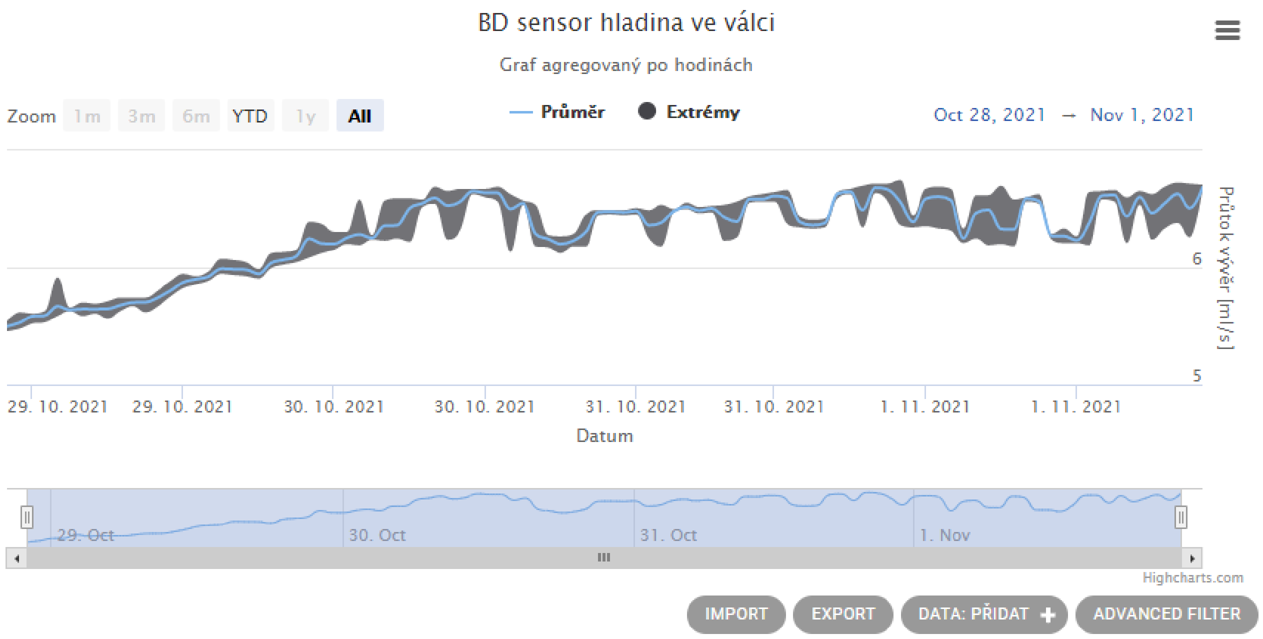

Fig. 14. An example of data presentation from the database web site – flow rate at V6, 1-hour average and min/max range in the same sampling.

Table 1. An accuracy overview of various probes (adopted from technical documentation).

Method	**working range [cm]**	**resolution [mm]**	**relative accuracy [%]**	**absolute accuracy [mm]**
US probe Turck S18UAI [15]	30	–	0.08	0.25
US probe US1200, Fiedler-Mágr [18]	120	1	0.2	2.4
pressure probe LMP307i, BD Sensors [14]	100	1	0.1	1
pressure probe Levelogger Gold/Edge, Solinst [19]	500	1	0.05	2.5
load string device Geokon [20]	15	0.04	0.1	0.15

significantly shorten the working life of the probe, since the membrane of the probe is in the open contact with water. On the other hand, they have very simple installation and higher-order measuring range. Levelogger probes have a longer service life than BD-Sensor probes (some of malfunctioning probes have been replaced after about 3 years of working). Presented accuracies for Levelogger probes suppose the ideal connection with the atmosphere or the perfect time coordination with the barometric logger, which is mostly not practicable.

Load string principle has an advantage in the very high absolute accuracy (with rather small working range). Its disadvantages lie in a rather difficult installation with considerable space demands and a need of the proprietary evaluation unit (it has not been connected to the presented online data collection system).

5 Conclusion

The presented measurement project demonstrated a heterogeneous telemetry system with various flow conditions and measurement principles. Generic units with configurable ethernet interface have been used, in contrast with a common use of proprietary protocols and data storage services provided by the measuring unit producers or supplier. The water level measurement was limited by the sensors' accuracy and durability, but the experience proved its value for observation and evaluation the temporal variations of groundwater discharge.

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