Groundwater

Methods Note/

Measuring Flow Rate in Crystalline Bedrock Wells Using the Dissolved Oxygen Alteration Method

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Abstract

Determination of vertical flow rates in a fractured bedrock well can aid in planning and implementing hydraulic tests, water quality sampling, and improving interpretations of water quality data. Although flowmeters are highly accurate in flow rate measurement, the high cost and logistics may be limiting. In this study the dissolved oxygen alteration method (DOAM) is expanded upon as a low-cost alternative to determine vertical flow rates in crystalline bedrock wells. The method entails altering the dissolved oxygen content in the wellbore through bubbler aeration, and monitoring the vertical advective movement of the dissolved oxygen over time. Measurements were taken for upward and downward flows, and under ambient and pumping conditions. Vertical flow rates from 0.06 to 2.30 Lpm were measured. To validate the method, flow rates determined with the DOAM were compared to pump discharge rates and found to be in agreement within 2.5%.

Introduction

In bedrock wells, vertical flow will occur when two or more transmissive fractures with different hydraulic heads intersect a borehole, creating a hydraulic head gradient (Paillet, 1998). Elci et al. (2003) showed that in screened wells, a strong downward flow may not be overcome through typical pumping rates during low flow sampling and may result in the complete neglect of a water-contributing zone (Church and Granato, 1996). Measurements of vertical flow rates in the wellbore can provide information about relative hydraulic gradients, which can improve hydraulic testing and aid in developing sampling techniques. Furthermore, flow rate measurements provide a measurement of fracture discharge, which is critical in accurately interpreting water quality sampling results.

Vertical flow rates in a well are commonly measured with flowmeters, such as the heat-pulse flowmeter (Hess, 1986; Paillet et al., 1987) or electromagnetic flowmeter (Molz et al., 1994). Other techniques for determining vertical flow rates include the analysis of temperature profiles (Bredehoeft and Papadopulos, 1965; Sorey, 1971; Ge, 1998; Klepikova et al., 2014) and other various tracer studies (Michalski and Klepp, 1990; Chlebica and Robbins, 2013). While temperature profile analysis has made much progress, small inaccuracies in measurements (such as changes in temperature with a horizontal shift in the probe in the wellbore) may result in incorrect flow assessment due to a low temperature gradient over the length of the wellbore (Klepikova et al, 2014). Heat-pulse flowmeter measurements can provide precise flow measurements ranging from 0.04 to 5.7 Lpm; however, equipment cost and logistics can be limiting. Tracer studies involve the addition of liquid tracer into the wellbore which can impact the ambient flow rate owing to changes in the water level in the well and tracer density.

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This study presents a highly sensitive and low-cost alternative for determining vertical flow rates in crystalline bedrock wells through dissolved oxygen (DO) alteration. The dissolved oxygen alteration method (DOAM) was developed by Chlebica and Robbins (2013) to identify transmissive fractures under ambient and stressed conditions. The original method involved increasing DO in the water column by bubbling air into a well using a porous polypropylene bubbler connected to a compressed air tank and monitoring changes in the DO profile with time. Depths where discrete DO dilution occurred showed locations of inflowing transmissive fractures. Vertical movement of the diluted zones showed vertical in-well flow direction. Chlebica and Robbins (2013) and Vitale and Robbins (2016) determined that flow was the primary factor in changing DO concentration and that the effects of biotic or abiotic reactions were negligible, in the time frame of testing. Gas tracers have two distinct advantages over liquid tracers. First, the injection of air into a well can be controlled to maintain the well's hydraulic head to prevent impacting flow conditions. Second, since the solubility of gases increase with increased pressure, a gas profile will increase with depth allowing vertical shifts in the profile (and therefore vertical flow) to be easily detected. This is reinforced with the injection technique of air rising from the bubbler, resulting in the highest concentrations occurring near the bubbler location and concentrations decreasing upward. That is, a profile will increase with depth even if saturation is not reached. Owing to increased DO solubility with depth, high DO values can be achieved making the method highly sensitive. DO is ideal compared to other gases due to ease of accessibility of DO sensors. The method is advantageous for testing drinking water wells because of its nontoxic nature. While other chemical tracers may have regulatory requirements on concentration and mass recovery requirements owing to their toxicity, air injection does not. Although Chlebica and Robbins (2013) provided estimates of flow rate using the original method, the estimates were based on the movement of the DO "front," which did not account for dispersion. The expanded DOAM described in this study focuses on obtaining highly accurate measurements of vertical flow rate by tracking the advective movement of DO.

Test Site

The test well (Sima 1) is located at the University of Connecticut in Storrs. Sima 1 is 15.2 cm in diameter and 94.5 m deep, drilled into the Hebron Gneiss. A steel casing extends 9 m deep through overlaying glacial till. Three transmissive fractures intersect Sima 1 at 16 m, 40 m, and 86 m. Heat-pulse flowmeter measurements did not detect ambient vertical flow (Cagle 2005); however, tracer tests (Libby and Robbins, 2012; Chlebica and Robbins, 2013) have demonstrated that under ambient flow conditions, the fractures at 16 m and 40 m are inflowing, the fracture at 86 m is outflowing, and that flow in the well is vertically downward.

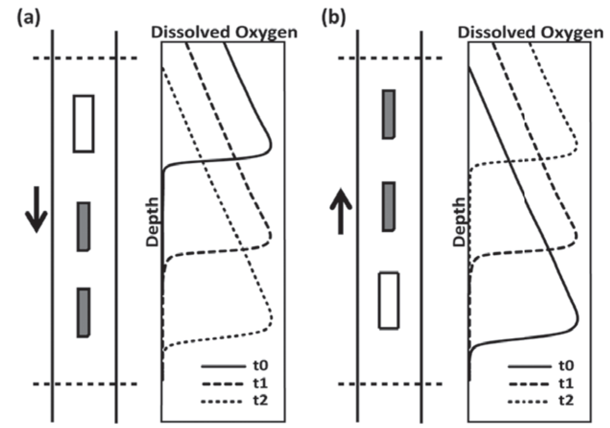

Figure 1. Instrument positioning and conceptual model of shift in dissolved oxygen (DO) concentration profile over time for (a) downward and (b) upward flow. The bubbler is shown in white and the DO sensors are shown in gray. Flow direction is indicated by the arrows. The dashed lines above and below the instruments represent transmissive fractures of different hydraulic heads. The solid, dashed, and dotted profile lines represent change in the DO profile at t_0, t_1, and t_2.

Method

Prior to the application of this method, it is ideal to have knowledge of transmissive fracture depths and vertical flow direction, which can be accomplished in minutes to hours (depending on flow rate) through the original application of the DOAM (Chlebica and Robbins, 2013). The expanded application of the DOAM for determining flow rate takes advantage of a DO profile that increases with depth. For downward flow (Figure 1a), air is bubbled into the upper part of the flow zone, and two DO sensors are positioned below the aeration depth at a set interval. Since the DO sensors are initially placed below the aerated portion of the well, initial (t_0) DO concentrations will begin as background concentrations. As downward flow occurs, the profile shifts (Figure 1a) and DO concentrations will begin to increase as the aerated portion of the water column approaches the shallower sensor (t_1). A peak is formed as the highest DO concentrations reach the sensor, followed by a decrease in DO as lower-DO water moves past the sensor. Continued downward flow will result in a second peak at the lower sensor (t_2). Although DO disperses as the water column migrates, the peak concentration migrates as a function of advection. The time elapsed between each peak is divided by the distance between the two sensors to calculate velocity. Velocity can then be converted to flow rate, given the radius of the borehole. Using two sensors minimizes in-well disturbance to get a more distinguishable peak at each sensor.

For upward flow, air is bubbled into the lower part of the flow zone, and two DO sensors are positioned above the aeration depth (Figure 1b). In this scenario, initial DO concentrations measured by the sensors (t_0) will not represent background concentrations, but will still be less than the maximum concentration due to decreased DO at shallower depths. As upward flow occurs, DO

Table 1
Instrument Positioning and Velocity Results for Downward Ambient Flow Conditions in Sima 1

Flow Zone	Bubbler Position (m below TOC)	DO Sensor Positions (m below TOC)	Time Elapsed Between DO Peaks (min)	Flow Rate (Lpm)
Upper (16–40 m)	18.3	19.2; 19.8	191	0.06
Lower (40–91 m)	50.3	53.4; 54.3	118	0.14

TOC, top of casing.

Table 2
Instrument Positioning, Total Drawdown, and the Time Elapsed Between DO Peaks for Each Pumping Test Conducted in Sima 1

Pump Flow Rate (mL/min)	Bubbler Position (m below TOC)	DO Sensor Positions (m below TOC)	Depth-to-Water (m below TOC)	Pump Position (m below TOC)	Total Drawdown (cm)	Time Elapsed Between DO Peaks (min)
275 ± 5	12.2	10.7; 9.8	4.48	4.75	13.1	61
895 ± 10	14.9	12.2; 9.1	4.42	6.25	84.1	61
1750 ± 20	14.9	12.8; 9.8	3.98	5.49	64.3	32
2300 ± 20	14.6	12.2; 10.7	4.53	6.00	75.2	12

TOC, top of casing.

concentrations will increase as the higher-DO water from below approaches the lower sensor (t_1). After the peak passes, DO decreases since water below the peak was unaerated. As with downward flow, flow rate is calculated from the elapsed time and distance between the peaks. It is assumed that DO concentrations are uniform across a horizontal cross section of the well since the horizontal positioning of the DO sensor in the wellbore cannot be controlled. The presence of the probe is assumed to have a negligible effect on DO concentrations. Based on testing in Chlebica and Robbins (2013) and Vitale and Robbins (2016), DO profile repeatability in stagnant zones indicates that mixing from density gradients does not have a measureable impact on vertical movement in the well over the course of hours to days, and is therefore assumed to be negligible relative to advective flow in the well in this study.

The procedure was tested in Sima 1 using two Instrumentation Northwest (INW) manufactured DO probes. Background DO concentrations in Sima 1 are less than 2 mg/L throughout the wellbore, which is sufficiently low for testing. Compressed air was injected into the wellbore from an ultra zero grade air cylinder connected to a porous polyethylene bubbler. Air injection rate and pressure were controlled by valves attached to the tank regulator. After aeration the INW DO sensors were positioned at the desired depths, and the DO probe cables were secured to the side of the wellbore to be certain the instrument would not move vertically during testing. Downward velocity was measured under ambient flow conditions in the upper and lower flow zones of Sima 1. The instrument positioning is shown in Table 1. For both the upper and lower flow zone tests, the well was aerated for 5 min. The short bubbling duration allowed DO concentrations to increase while minimizing the amount of time for ambient flow to occur during aeration.

Velocity tests were then conducted in Sima 1 while pumping to investigate the application of the DOAM for upward flow. This also provided a means for verification of the DOAM by comparing calculated DO flow rates to measured pump discharge rate, and allowed a range of velocities to be tested. Tests were conducted above the upper 16-m fracture (stagnant zone). The fractured zones were purposely avoided so that flow rate measured in the well with the DOAM should be equal to the pump discharge. The bubbler and DO sensors were positioned above the fracture (Table 2). The well was aerated for 5 min. The pump was positioned near the top of the water column to induce upward flow. The positioning of the lower DO sensor relative to the bubbler was selected so the water level would reach steady-state by the time the DO peak reached the first sensor to ensure an accurate velocity reading. Pump discharge rates were measured several times after reaching steady-state using a 1000-mL beaker and a stopwatch to be certain the flow rate remained constant. The test was conducted for discharge rates of 275 mL/min, 895 mL/min, 1750 mL/min, and 2300 mL/min.

Best Practices and Potential Limitations

As described above, air injection rates should be controlled so there is no change in water level. Air injection pressure is determined by the amount of water pressure overlying the bubbler. For example, if the bubbler is positioned 6 m below water, the air pressure should slightly exceed 8.5 PSI to overcome the water pressure. A pressure much higher than water pressure should be

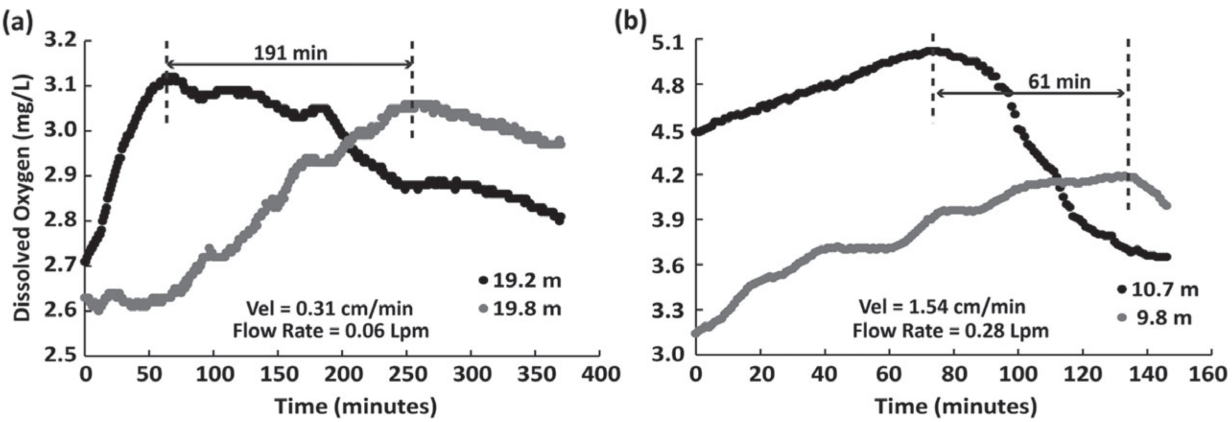

Figure 2. Examples of DO measurements obtained during (a) downward and (b) upward flow in Sima 1. Velocities are calculated from change in time and distance between maximum DO concentrations at each sensor and converted to flow rate using the wellbore cross-sectional area.

avoided as it will result in a rise in the water column, which will change in-well flow conditions.

Knowledge of background DO concentrations can provide information on the suitability of the DOAM for a particular well. In wells with shallow-fed fractures (typically high DO background concentrations), near surface applications of the DOAM may be limiting since aerated concentrations may not differ greatly from background concentrations. It is equally important to control DO concentrations to ensure they do not exceed the detection limits of the DO sensor being used. This is typically an issue specific to aerating deep in the well for long durations. In the method described in this study, the short bubbling duration prevented this for the sensor used (INW DO Sensor), which had a detection limit of 25 mg/L. For cases where this may present a concern, the DO sensor can be positioned nearby the bubbler during aeration to monitor DO levels and ensure they do not exceed detection limits.

The addition of DO to a well may not be ideal where alteration to redox conditions may result in toxic conditions; however, due to the short duration of aeration in the DOAM, DO, and redox conditions typically return to background conditions within hours to days in wells where flow is not very slow or stagnant.

Although knowledge of flow direction is helpful, there may be situations where flow direction varies or is unknown. In this case, DO sensors can be positioned above and below the bubbler to monitor changes in DO concentration and determine vertical flow direction in addition to quantifying flow rate.

Results and Discussion

Figure 2 shows DO measurements recorded for downward (ambient) and upward (pumping) flow in the upper flow zone of Sima 1, which demonstrates the flow rate calculation from the advective movement of the DO over time. Ambient flow rates in the upper (16 to 40 m) and lower (40 to 86 m) flow zones are shown in Table 1.

Table 3
The Results of Pumping Velocity Tests for Comparing DOAM Flow Rate and PUMP FLOW Rate

DOAM Flow Rate (mL/min)	Pump Flow Rate (mL/min)	% Difference
282 ± 5	275 ± 5	2.5 (6.3)
911 ± 15	895 ± 10	1.8 (4.6)
1738 ± 55	1750 ± 20	0.7 (4.9)
2315 ± 90	2300 ± 20	0.7 (5.5)

Errors for the DOAM and pump flow rates are associated with temporal resolution. The third column shows the % difference between the DOAM and pump flow rate, with the maximum % difference accounting for temporal resolution errors in parenthesis.

Pumping test results are shown in Table 3. Since DO concentrations were recorded once per minute, the error range listed with the DO flow rate accounts for the DO peak passing the sensor within one minute before or after the recorded peak. This error decreased with lower flow rates, or with larger spacing between DO sensors (i.e., longer peak-to-peak times). Flow rates calculated with the DOAM agreed with measured pump discharge rates within 2.5% (6.3% accounting for errors).

In these tests, flow rates measured using the DOAM were within the range of detectability of a heat-pulse flowmeter; however, the DOAM is advantageous in the ability adjust sensitivity for various flow conditions. In wellbores with a low flow rate, spacing between sensors can be increased to reduce error. For high flow rates or short flow zone distances between transmissive fractures, frequency of measurements can be increased.

Conclusion

The DOAM provides a highly sensitive, low-cost means for characterizing flow conditions in bedrock wells. Coupled with the initial application of the DOAM for identifying transmissive fractures and determining vertical flow direction, this new approach enhances the application of the method by providing accurate measures of vertical borehole velocity, and the ability to adjust measurement sensitivity for various flow conditions. The low cost and logistical simplicity may provide an advantage over traditional methods in measuring borehole flow.

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