

Boise State University

ScholarWorks

Geosciences Faculty Publications and
Presentations

Department of Geosciences

8-27-2021

Fiber Optic Pressure Measurements Open Up New Experimental Possibilities in Hydrogeology

Carsten Leven
University of Tübingen

Warren Barrash
Boise State University

Publication Information

Leven, Carsten and Barrash, Warren. (in press). "Fiber Optic Pressure Measurements Open Up New Experimental Possibilities in Hydrogeology". *Groundwater*. <https://doi.org/10.1111/gwat.13128>

© 2021 The Authors. *Groundwater* published by Wiley Periodicals LLC on behalf of National Ground Water Association.

Fiber Optic Pressure Measurements Open Up New Experimental Possibilities in Hydrogeology

by Carsten Leven¹  and Warren Barrash²

Abstract

Fiber-optic (FO) technology is being used increasingly for measurement methods in a variety of environmental applications. However, FO pressure transducers are rarely used in hydrogeological applications. We review the current state of Fabry-Pérot interferometry-based FO pressure transducers, including their advantages and limitations, as another option for high-resolution pressure- or head-change measurements in conventional or advanced aquifer testing. Resolution and precision specifications of FO transducers meet or exceed commonly used non-FO pressure transducers. Due to their design, FO transducers can be used in small-diameter (inner diameter $\geq 1/4$ inch) and continuous multichannel tubing (CMT), sampling points, multilevel packer systems, and Direct Push-based in situ installations and testing. The small diameter of FO transducers provides logistical advantages—especially for tests with monitoring at many zones in a number of wells and/or CMTs (e.g., no reels, placement just below water level in access tubes vs. within isolated zones, reduced weight and volume, small footprint at single point of data acquisition). Principal limitations are small measurement drift that may become evident for tests longer than a few hours, and higher-than-average cost. We present field examples of FO transducer performance in short-term tests with high consistency of acquired data and higher resolution (i.e., capturing significant hydrologic information) compared with commonly used non-FO transducers. Given the above, including advantageous logistical features, FO transducers can open new experimental possibilities in areas of high-resolution three-dimensional (3D) heterogeneity (flow and transport, remediation, critical zones); 3D fracture networks and fundamental hydromechanical behavior; complex 3D flow and leak detection (mines, dams, repositories, geothermal systems).

Introduction

Most hydrogeological investigations require the acquisition of hydraulic head information, which is

¹Corresponding author: Center for Applied Geoscience, Hydrogeology, University of Tübingen, Tübingen, Germany; carsten.leven-pfister@uni-tuebingen.de

²Department of Geosciences, Boise State University, Boise, ID
Article impact statement: We discuss the performance of Fabry-Pérot fiber optic pressure transducers in hydrologic tests along with new experimental possibilities.

Received January 2021, accepted August 2021.

© 2021 The Authors. *Groundwater* published by Wiley Periodicals LLC on behalf of National Ground Water Association.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

doi: 10.1111/gwat.13128

often gathered as time series during hydrological tests. In particular, efforts to determine the distribution of hydraulic conductivity at high resolution, such as slug tests, interference tests, or hydraulic tomography, require highly resolved measurements of water-level changes. A wide range of state-of-the-art transducers for measuring water-level changes are available (Tamari and Aguilar-Chavez 2010; Sorensen and Butcher 2011) such as piezoresistive, piezoelectric, and strain-gauge transducers (Dyer 2004). In this regard, pressure transducers commonly have dimensions that fit into 2 inch-wells (50 mm inner diameter [ID]). Transducers with diameters in the range of 0.5 inch (12 mm) that fit into 1 inch-wells (25 mm ID) are less common but are also available.

The use of fiber-optic (FO) pressure transducers in hydrogeological applications was first proposed by Butler

et al. (1999) in multilevel wells for hydraulic tomography. They stated that the costs (at that time) of FO equipment impeded their practical utility. However, this has changed considerably and FO equipment is used broadly in medical and engineering applications. However, the use of FO pressure transducers (hereafter: FO transducers) is still rare for hydrogeological applications.

In this Method Note, we discuss the current state of Fabry-Pérot interferometry (FPI)-based FO pressure measurements for hydrogeological applications. After presenting basic principles, and design, measurement, and logistical aspects, including advantages and limitations, we show results from several field experiments to highlight performance capabilities of this technology. In this regard, FO transducers provide an instrumentation option for routine applications, and especially for high-resolution three-dimensional (3D) aquifer characterization, that meets or exceeds non-FO high-performance transducers and which can open up new experimental possibilities with moderate costs.

Principle of Fiber-Optic Pressure Measurements

FO sensors are widely used for many different tasks in the fields of medicine, engineering, and environmental applications (e.g., Yin et al. 2008; Udd and Spillman 2011). In environmental research, FO sensors are used for monitoring suspended sediment on the seafloor, in situ monitoring of contaminants in groundwater, investigation of stream dynamics, soil moisture and humidity sensing, among others (Beach et al. 1992; Buerck et al. 2001; Westhoff et al. 2007; Yeo et al. 2008; Sayde et al. 2010; Becker et al. 2013; Benitez-Buelga et al. 2014; Sebok et al. 2015; Halloran et al. 2016). Point sensors, which measure a physical property (temperature, pressure, strain) at a particular point, are among the most widely used FO sensors. In contrast, distributed sensors measure the change of a physical property along all, or a certain part, of an optical fiber (e.g., Bao and Chen 2012; Zhang et al. 2021).

For measuring pressure with point sensors, FPI is used. FPI is based on the design of two partially translucent, parallel mirrors with a separating distance forming a gap (i.e., FPI cavity). Incident light undergoes multiple reflections in this FPI cavity while, after each reflection, a small fraction of the light escapes through the mirrors resulting in constructive interference of many parallel light beams that produce sharp interference fringes when led through a lens onto a screen. In the interference pattern, the distance between the fringes depends on the light wavelength, refraction index, and optical path length—which is directly related to the spacing of the FPI cavity—which, in turn, is directly related to pressure. Comprehensive descriptions of FPI technology can be found in Tolansky (1973); Ball (2006); Yu and Zhou (2011), among others.

Roriz et al. (2013) list companies that commercialize FO transducers. Although the list mainly refers to

biomedicine, it also includes FO pressure systems that can be used in industrial and environmental applications. Here we note that brand and model information on FO systems in examples of hydrogeological applications discussed later are for descriptive purposes only, and do not imply endorsement by the authors.

Design and Measurement Aspects of Fiber-Optic Pressure Transducers

In the following section, we discuss major aspects of the design and operational characteristics of FO pressure transducers for hydrogeological applications (also summarized in Table 1).

Measurement System

FO systems typically consist of three main parts: (1) the sensor or FO transducer, (2) the light and signal conditioning unit, in which the incoherent light is generated and the light returning from the sensor is collected, and (3) the data acquisition unit, to convert and record the data. Typically, commercially available systems are easy to setup as they use industrial standard components. As all electronic components are contained in the conditioning and data acquisition units, the pressure transducer itself can be emplaced in harsh environments, such as high (geothermal) temperatures or electromagnetic fields (in close proximity to pumps) which can be problematic for other types of transducers.

Though the use of FO systems is relatively straightforward, they are high-performance devices that need careful handling—even though the robustness of the transducer and fiber cables is increased by probe-like stainless steel armoring at the tip, along with flexible steel armoring from the probe-like tip to the end of the transducer cable (Figure 1a—transducer 1). In this regard, FO transducers can last many field seasons with reasonable attention to common practices such as: (1) cleaning coupling pieces to avoid dirt and dust that could reduce data quality or damage parts of the FO system; and (2) avoiding bending, crushing, pinching, or dropping that may break the fibers or the transducer itself.

The increasing availability and use of the various FO measurement techniques overall have also resulted in more favorable costs of such systems, with cost reduction by about a factor of four compared to costs discussed by Butler et al. (1999). Currently, FO systems are available that—even though above average—can compete in price with small-diameter, high-precision, non-FO, pressure transducers in use for hydrologic testing and monitoring.

Fiber-Optic System Components

For FO pressure measurements, multimode fibers are typically used with a continuously decreasing index of refraction from the core axis to the cladding. For application in hydrogeological testing, these fibers have the advantage that, due to the larger diameter in comparison to single-mode fibers, the connection of fibers is simplified, and inexpensive sources of incoherent light such as

Table 1
Summary of Design and Operational Aspects of Fiber-Optic Pressure Transducers

Component	Characteristics and Advantages	Limitations
Measurement system	<p>Easy-to-setup system with light/signal conditioners; all transducers connect to a single DAQ system.</p> <p>Insensitive to electromagnetic fields, e.g., when transducer is operated attached or close to a submersible pump.</p> <p>FO transducers can compete in price with commonly used high-precision pressure transducers in use for hydrologic testing</p>	<p>Careful handling of transducer connections and cables required.</p> <p>System not suitable for operation in remote locations or widely spaced observation locations due to operation of light/signal conditioners.</p>
Fiber-optic components	<p>Easy connection options due to relatively large diameter of the fibers (i.e., compared to single mode fibers).</p> <p>Inexpensive white light LED for light source.</p> <p>Extension FO cables available at custom lengths (e.g., 25, 50, up to 150 m)</p>	<p>The optical connections are susceptible to the influence of dirt and dust; however reasonable care essentially removes this issue</p>
Fiber-optic transducer	<p>Transducer in a stainless steel housing with small dimensions (diameter: 3-6 mm, transducer length: 30-50 mm); housing tip design protects transducer but avoids air bubble entrapment.</p> <p>Wide span of pressure ranges available</p> <p>As transducer needs only be placed just below the expected change in water level in the piezometer, a smaller range within a given transducer's pressure rating can be selected by the user for each transducer (in the lab or in the field), and thereby improve accuracy and resolution.</p> <p>Sampling rates up to 125 Hz (manufacturer standard), other DAQ systems allow sampling in bursts or log cycles.</p> <p>Use of armored cable to reduce fragility of FO cables and allow easy insertion into small-diameter tubing</p>	<p>Long-term drift has to be evaluated for the specific measurement environment and duration (e.g., longer than several hours).</p> <p>Absolute pressures are measured and thus require the acquisition of atmospheric pressure to make corrections, as needed.</p> <p>Check with manufacturer on temperature ranges, currently standard up to 80°C, higher temperature ranges can be available</p>
Installation and fields of application	<p>Easy to install and remove with packer systems, multichannel tubing, and other small-diameter observation wells especially in combination with Direct Push techniques.</p> <p>No pressure-tight seals or placements needed at deep zone levels.</p> <p>Advantageous for hydrologic testing which requires high resolution and fast sampling capability.</p> <p>Efficient storage, shipping, on-site use due to small cable size and weight, ease of coiling and uncoiling vs. need for reels.</p> <p>Small footprint at transducer-DAQ interface and single device (laptop) for control, recording, feedback—even with 30 to 40 transducers or more.</p> <p>Optional analog signal output allows integration into user-specific data acquisition units</p>	<p>Use of guiding tubes in larger wells is recommended to protect the transducer cable from entangling with in-well equipment.</p> <p>Due to possible long-term drift, currently most suitable for hydrologic testing with durations of a few hours.</p> <p>If significant temperature variation is expected, review temperature dependency from manufacturers</p>

LED can be used. Although multimode fibers have lower sensitivity than single-mode fibers (Totsu et al. 2005), FO systems using multimode fibers still have significant sensitivity advantage over most other (non-FO) types of transducers noted above. Also, all optical connectors are susceptible to the influence of dirt and dust, which can typically be recognized by noisy data, and can be avoided or fixed with reasonable care during the installation and removal processes.

Fiber-Optic Transducers

The FO transducer is that part of the system which is directly exposed to the measurement environment. The pressure head is measured at the transducer tip which is submerged below the piezometric surface or water level in an observation well or measurement tube. Due to the principles of fiber optics, the transducer tip can be constructed with a minimal diameter. For the system

we discuss here, the transducer is placed in a stainless-steel tube commonly with a length of 30 to 50 mm. In addition, the extension fiber can be armored in a flexible stainless-steel mantle which significantly reduces the fragility of the fiber, and also facilitates threading of the small-diameter cable through small-diameter access tubes in wells or packer systems. At its thickest place (i.e., the fusion-covering between the steel tube and the cable extension), the transducer cable has a diameter of 3 to 6 mm, depending on the type of cable and transducer tip. These small transducer dimensions therefore allow their use in numerous types of small-diameter access tubes and specialized observation wells, which opens up new experimental possibilities (see details in the following sections). For comparison, Figure 1a shows a FO transducer (1) against other commonly available transducers (2) to (4), which all have diameters less than 25 mm (1 inch). Figure 1b is a close-up view of two types

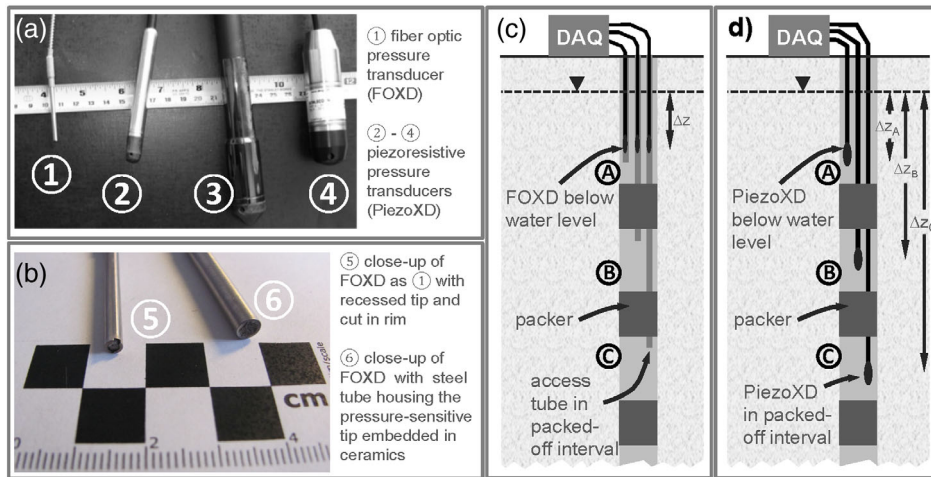


Figure 1. Comparison of different pressure transducers and examples of two possibilities for the placement of pressure transducers in a well with a packer system for hydrologic testing: (a) Photograph of different pressure transducers: (1) FISO Inc., model FOP-MIV-NS-369D, OD: 6 mm, (2) STS Sensors, model MTM/N10 OD: 10 mm, (3) Schlumberger Water Services CTD Diver, (4) STS Sensors, model MTM/N10, OD: 24 mm. (b) close-up of two types of fiber-optic pressure transducers (FOXD). (c) Example for the placement of FOXD in a well with packers and three monitoring zones A, B, and C. The monitoring zones are connected by tubes to the surface and the FOXDs are only placed Δz below the water level in the tube for all monitoring zones. (d) Nonoptical pressure transducers (as shown in (a)) typically need to be placed directly in the monitoring zones, with pressure-tight seals, in different depths Δz_A , Δz_B , Δz_C due to their dimensions.

of FO transducer probe tips: (5) with a recessed tip and cut in the rim to avoid air bubble entrapment at the pressure-sensitive tip of the transducer, and (6) with a Kevlar-enforced polyurethane cable and a steel tube housing the pressure-sensitive flat tip embedded in ceramics.

Due to the small dimensions of the FO transducers, they can be used in miniaturized piezometers or sampling tubes with diameters as small as 6.35 mm (1/4 inch ID), and they do not have to be placed directly in the measurement zone. In this regard, Figure 1c and d give examples for the use of FO versus non-FO transducers: a packer system is used to separate different monitoring intervals (e.g., during hydraulic tomography or other multilevel testing). The FO transducer is placed in a small-diameter tube which connects to the packed-off interval and functions as a piezometer to access the hydraulic head in that zone. The transducer can be placed just below the water level in the tube, while a non-FO transducer (due to the larger dimensions) typically needs to be placed directly in the observation zone with attendant pressure-tight sealing and sufficient cable length back to a data logger. This means a small pressure range (full-scale range) for the FO transducers can be selected by the user, as the transducer itself only has to be placed below the water level with sufficient head above for expected water-level change during testing (e.g., measurement ranges $\Delta z_{A,B,C}$ for piezoresistive transducers vs. Δz for FO transducers in Figure 1c and 1d). That is, accuracy, precision, and resolution are not sacrificed for monitoring zones progressively deeper below the water level—for which larger dynamic ranges are needed for transducers sealed in deeper monitoring zones.

For FO pressure transducers, a wide measurement range is available with accuracy, precision, and resolution

comparable to or exceeding non-FO transducers. For the latter, Sorensen and Butcher (2011) reported accuracy within 1% to 2% of full scale and precision within a few millimeters for lower pressure-range transducers. Cardiff et al. (2013), Hochstetler et al. (2016), Sanchez-León et al. (2016) and Tiedeman and Barrash (2020) have shown resolution of drawdown to less than 1 mm by using reduced (i.e., user selected) calibration range and averaged measurements over very short time intervals (“burst sampling” or “oversampling”—see field examples below).

Here we note that FO transducers make total head measurements and hence require accompanying atmospheric pressure measurements for adjustment of field data to remove atmospheric effects before use of data in hydrologic analysis. Such corrections are the same as needed for other transducers that measure total pressure.

Installation and Applications

Besides the advantages of an optimized measurement range, the small dimensions of FO transducers and cables allow their use in different types of wells and piezometers. They can be installed easily with dedicated small-diameter access tubes in isolated zones of packer systems (e.g., Figure 1c), in continuous multichannel tubing (CMT, e.g., Einarson and Cherry 2002; Hochstetler et al. 2016; Sánchez-León et al. 2020), and other small-diameter observation wells which can be installed efficiently with Direct Push techniques (e.g., Dietrich and Leven 2006; Leven et al. 2011). Additional logistical benefits include: availability of FO extension cables at custom lengths (up to 150 m) to allow greater distances between wells and a DAQ station; easy coiling-uncoiling of FO cables to avoid the need for reels; and smaller volume and weight

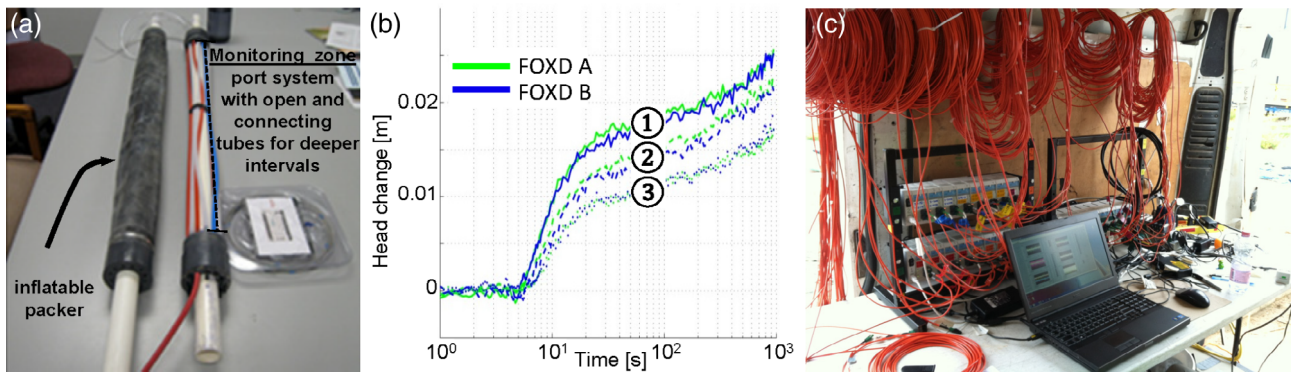


Figure 2. (a) Photograph of a packer-and-port system as it is used at the BHRS in combination with FO transducers and setup as illustrated in Figure 1c. Hydraulic contact to the zone under investigation is achieved by tubing in which the FO transducers are only lowered $\Delta z \approx \text{max. } 1 \text{ m}$ below the water level. (b) Data collected during three hydraulic tomography pumping tests (curves labeled 1, 2, and 3) at the BHRS. The drawdown data was recorded by two FOXDs (labeled A and B) installed in a single tube connected to a single sampling interval during the three pumping tests (adapted from Cardiff et al. 2013 with permission of John Wiley & Sons Inc.). (c) Photograph of a typical field setup of a FO system with 35 attached transducers and extension cables (orange); note the small volume of the large amount of transducer cables.

per transducer and cable to reduce storage, transport, shipping space and costs—and to allow small footprints at the interface of many transducers plugged into modular, expandable light/signal conditioning units at one DAQ system (Figure 2c).

This flexible use opens up a wide range of field of applications, though the most suitable applications may be for high-resolution hydrogeological testing which requires high-resolution head-change and temporal measurements, such as for: (1) pumping and slug testing in formations with high hydraulic conductivity, for which fast aquifer responses can be expected; and also (2) low hydraulic conductivity including leaking aquitards adjacent to aquifers, where recognition of small responses may otherwise be missed; and (3) hydraulic tomography or hydromechanical testing where small head changes, and small differences in head changes between zones, are significant. We discuss these in more detail later with examples in section “Discussion of New Experimental Opportunities.”

Measurement Considerations

In this section, we present examples from hydrologic testing at several sites to demonstrate the performance of FO transducers under field conditions with respect to consistency and resolution. The examples will also show the logistical flexibility of using FO transducers with different piezometer and monitoring systems. For all cases, the same type of FO transducer system was used, however with different pressure ranges (cf., Table 2) and configurations of monitoring points and wells.

Data sets were collected at the Boise Hydrogeophysical Research Site (BHRS) in Boise (USA) in wells equipped with multilevel packer systems; at the Lauswiesen Hydrogeological Research Site (LHRS) in Tübingen (Germany) in different specialized piezometers installed with Direct Push technology; at a contaminated

site on southern Sardinia (Italy) using the same FO equipment as for the BHRS and the LHRS but in CMTs; and at the contaminated Naval Air Warfare Center (NAWC) in New Jersey (USA) with several types of multilevel packer systems in cored wells in fractured rock. The settings of the field sites are described elsewhere (BHRS: Barrash and Clemo (2002); LHRS: Lesoff et al. (2010); Sardinia: Hochstetler et al. (2016); NAWC: Tiedeman et al. (2010)).

The data set from the BHRS was collected during transient 3D hydraulic tomography experiments. The testing included a series of discrete multilevel pumping tests with multiple observation wells as described in Cardiff et al. (2013). Each observation well was equipped with a packer-and-port system for separating up to eight monitoring intervals (Figures 1c and 2a). In this packer-and-port system, the FO transducers are inserted in small-diameter tubes (6.35 mm or 1/4 in ID) connected to individual monitoring zones. Typically, each FO transducer is positioned only a few decimeters below the largest head change to be expected such that the FO transducers had a user-selected full-scale pressure range of $\sim 2 \text{ m}$ water head (3 psi). According to the manufacturer specifications this would result in a theoretical accuracy of 10.1 mm and a resolution of 1.31 mm (Table 2).

Measurement Consistency Between FO Transducers

Figure 2b shows an example of drawdown curves acquired during three pumping tests (1), (2), and (3) with different pumping locations and rates (Cardiff et al. 2013). Drawdown monitoring was performed with two FO transducers (FOX D A) and (FOX D B) in a given observation interval. The root mean square difference between transducer readings recorded during the different tests was less than 1 mm in all cases, thus reflecting a high degree of consistency of the system (factory-calibrated FO transducers and light conditioners) under field conditions. Also it can be seen that drawdown can be resolved

Table 2
Summary of the Specifications and Performance of the Fiber-Optic System During Field Measurements

Manufacturer Specifications			Typical Performance in Field Experiments		
Pressure Range ¹	Resolution ±0.065% ²	Accuracy ±0.5% ²	Resolution	Accuracy	Trend
LHRS ¹ : 5.0 m (0.5 bar)	3.25 mm	25 mm	<2 mm	could not be determined with lab and field experiments, typically not relevant for hydrologic testing that uses head change	usually not observable during our field tests due to test durations of <2 h, and for each test a resetting and restart of the data acquisition occurred
BHRS ¹ : 2.02 m (0.21 bar)	1.31 mm	10.1 mm	<1 mm		

¹ LHRS = Lauswiesen Hydrogeological Research Site (Tübingen, Germany), BHRS = Boise Hydrogeophysical Research Site (Boise, USA), latter system was also partly used at the LHRS and other sites as published in Hochstetler et al. (2016) and Tiedeman and Barrash (2020).

² Percentage referring to full scale; resolution as smallest measurable pressure change; accuracy as maximum absolute difference between true and measured pressure.

in the mm-range, with consistent lag times to onset of drawdown.

Performance in Various Direct-Push Installations

Experiments at the LHRS were conducted to examine the suitability of using FO transducers with different Direct Push-based installations to monitor hydrologic tests. The FO system used here had a pressure range of 5 m water-head full scale (Table 2). As shown in Figure 3, three different types of Direct Push wells were installed at distances between 1.0 and 2.5 m from a fully screened 6 inch pumping well (PW): (1) a CMT was configured for observations at seven depth intervals either 0.5 or 1 m apart (MC in Figure 3); (2) two temporary Direct Push groundwater samplers with a screen diameter of 1.5 inch and a length of 0.5 m allowed the observation of head responses within the Direct Push probe rod (DP); (3) two polyethylene tube piezometers (TP) were customized with short screen sections (5 cm length) at the tube end, which were covered by a fine mesh (125 μm) to prevent fine material from entering the tube. All three of the above types of monitoring points can be installed easily with Direct Push technology.

A short-term pumping test from well PW resulted in the head-change responses shown in Figure 3. The measurements show high resolution of time and drawdown with clear variations in the first arrival of the drawdown signal and the magnitude of drawdown at the different observation points (i.e., due to different interwell distances and aquifer heterogeneity). That is, clear drawdown differences in the mm-range, and time differences for drawdown responses in the subsecond range, can be resolved. This is most evident for responses recorded in the MC-well due to the larger number of sampling points at different elevations, but it can also be seen in the other two well types.

This test also illustrates the quality and value of the high-resolution drawdown and time data with regard to the clearly resolved peak at around 0.25 s in the PW. This short pressure disturbance is the result of powering the submersible pump, and can be recorded

by a FO transducer without any disturbance caused by the electromagnetic field induced by the pump itself. This pressure pulse also generated an oscillatory response clearly recorded in at least one of the observation wells (DP-well in Figure 3). Such responses are usually only seen as noise due to typically larger temporal sampling intervals, and the aliasing effect of such larger sampling intervals on subsecond behavior. This oscillatory behavior is similar to responses to slug tests in aquifers with high hydraulic conductivity and inertial effects of the moving water column in an observation well (e.g., Kipp 1985).

To examine the information potential of this testing configuration with FO transducers, the drawdown trend was removed and then the oscillatory head response was analyzed as a multiwell slug test (Butler and Zhan 2004). The resulting hydraulic conductivity of 3.3×10^{-3} m/s is similar to that from independent hydrologic testing at the site (e.g., Lessoff et al. 2010). In summary, the combination of Direct Push wells with FO transducers opens up new possibilities for the monitoring of hydraulic tests with low-cost easy-access installation, as well as for valuable detail on small differences in arrival times and drawdown magnitudes that provide meaningful hydrologic information on hydraulic parameters and heterogeneity that is otherwise below the detection limit of commonly used non-FO transducers.

Resolution, Sampling, Filtering

The examples in Figure 4a and 4b show drawdown data collected with FO transducers at a contaminated industrial site in Sardinia (Italy). The data illustrate a range of responses in drawdown magnitude, time lag to drawdown initiation, and curve shape for pumping tests performed during 3D hydraulic tomography testing. These data further highlight both the very high spatial and temporal resolution of FO transducers, and the logistical attributes that enable efficient deployment and operation of more than 30 FO transducers. This example from Hochstetler et al. (2016) shows drawdown responses recorded in observation intervals at different depths and distances from a given pumping interval. In this case, the

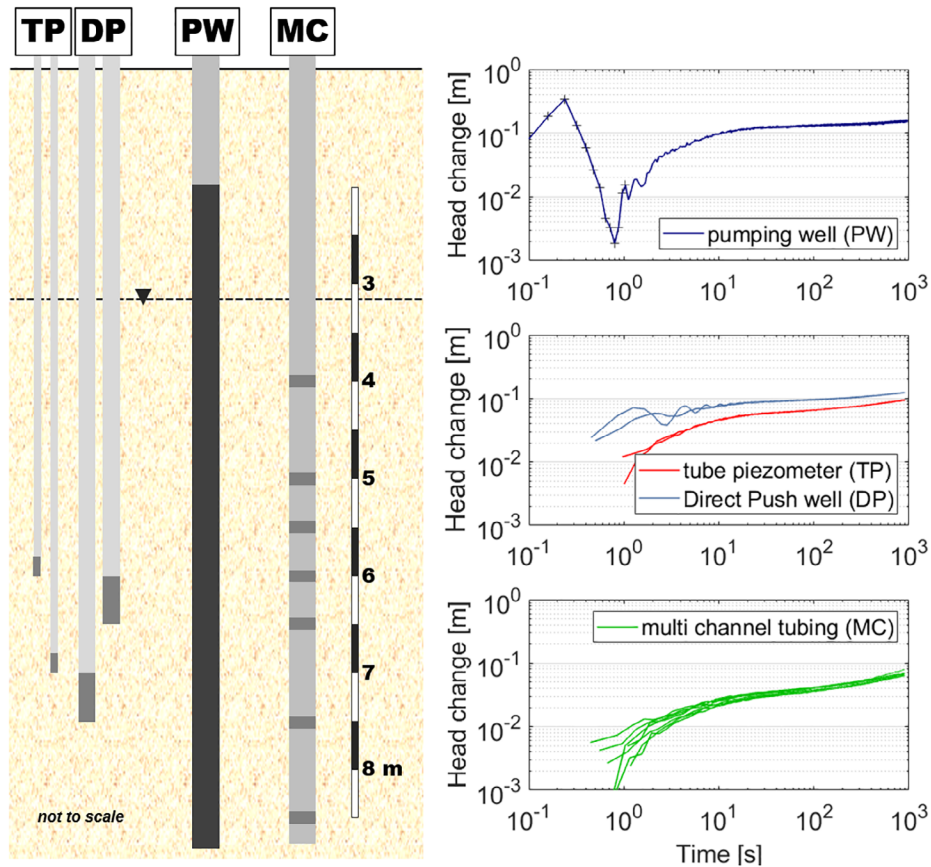


Figure 3. Sketch of the pumping test setup at the LHRs with Direct Push-based monitoring points (left) and responses of FO transducers to pumping (right, from top to bottom): in the 6-inch fully screened pumping well (PW, $Q = 5.7$ L/s); in two temporary Direct Push (DP, blue lines) sampling devices (ID 16 mm), two tube piezometers (TP, red lines) (ID 8 mm); and in a multichannel (MC, green lines) tubing with seven channels (ID 12 mm). Distance between PW and MC is 1 m; distances between PW and TP, and between PW and DP are 2.5 m. Note the head-change peak in PW and oscillatory behavior in one of the DP wells is due to a pressure pulse immediately after the start of the submersible pump.

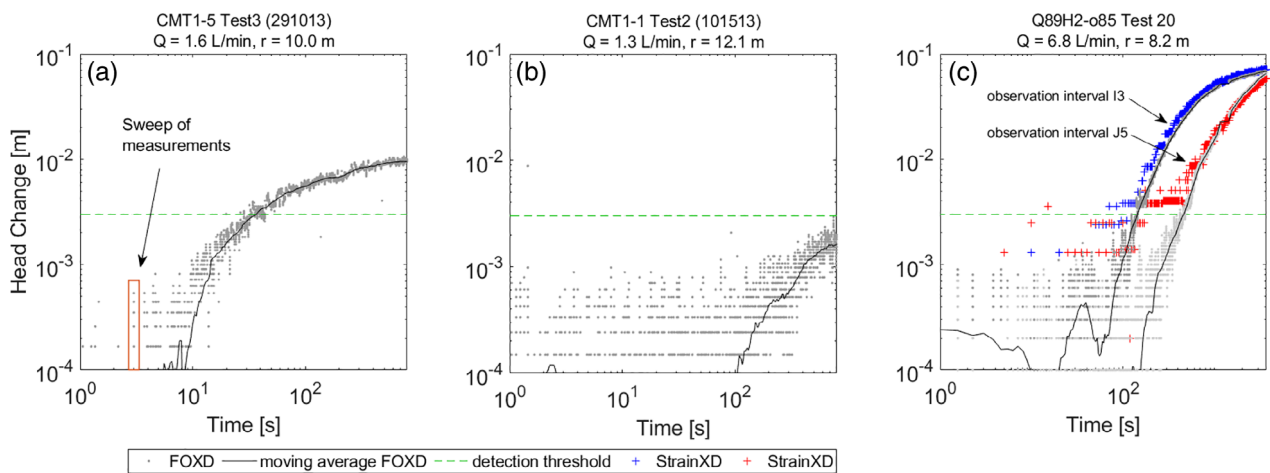


Figure 4. Drawdown data recorded during different tomographic pumping tests ($Q =$ pumping rate, $r =$ distance to pumping well). In (a) a sweep of consecutive head measurements is highlighted (“burst measurements”); in all panels, bursts are averaged to achieve higher resolution curves and identify when drawdown emerges from the less than 1 mm pre-drawdown noise. The horizontal green lines indicate the resolution or detection limit (~ 3 mm) of a commonly used non-FO pressure transducer. (a) and (b) Drawdown curves in CMT wells with FO transducers (data from Hochstetler et al. 2016) show that a significant portion of drawdown in (a) and all the drawdown in (b) would be missed by a non-FO transducer. (c) Comparison of drawdown data recorded by FO transducers (FOXD, model Figure 1) and strain-gauge transducers (StrainXD, model: GE Druck model PDCR 35D-10psig) paired in two observation zones of a packer system in a cored well at NAWC (data from Tiedeman et al. 2019); non-FO transducers miss the actual lag time to initiation of drawdown and early drawdown behavior, but show good matches to FO transducers above their detection limit.

pumping was conducted in a given zone in a CMT, while other zones and CMTs were used for observation (e.g., “MC” in Figure 3).

To achieve the highest resolution with the FO system, several straightforward approaches can be applied as in the above-described examples: “burst sampling” was used for data acquisition at the BHRS, Sardinia, and NAWC sites; “oversampling” was used at the LHRS with data acquisition rates of 2.5 to 100 Hz (400–10 ms).

For burst sampling, a sweep of data points is recorded with a very high frequency (e.g., 100 Hz), as highlighted in Figure 4a. Here for every acquisition time step, a sweep of, for example, six or eight measurements is taken within ~10 ms. Subsequent averaging of each burst filters noise and leads to a smoother curve reflecting head changes with higher resolution than that of the individual recorded values.

For oversampling, a fast acquisition range is used (e.g., 10 to 2.5 Hz), especially during the first minutes of aquifer testing. Even though short signal fluctuations might be in the range of a few millimeters (and include transient pumping-rate variations as well as FO measurement variability), the application of data filtering, smoothing and/or averaging can lead to a significant improvement of measurement resolution. For example, Sanchez-Léon (2018) and Sánchez-León et al. (2020) applied smoothing functions and low-pass filters to hydraulic (and tracer) test data to improve their signal-to-noise ratio. With this smoothing, Sanchez-León et al. (2016) could resolve drawdown signals in the range of 1 to 2 mm recorded with FO transducers that only have a theoretical resolution of more than 3 mm (cf., Table 2). These smoothing functions and filters can of course be applied to data sets acquired with burst sampling also.

Together with a high sampling rate, it is therefore possible to capture small drawdowns (less than 1 mm), and small differences in drawdown and drawdown initiation times between different intervals. Such distinctions are especially important: (1) in high-conductivity formations; (2) for analyzing drawdown data showing fast-responses, small head changes, and/or small but significant head-change differences between zones or wells, such as during multiple-zone and/or multiple-well slug or pumping tests (including 3D hydraulic tomography experiments, e.g., see Figure 3 in Cardiff et al. 2012); and (3) to improve estimates of specific storage, in recognition of greater sensitivity of drawdown to specific storage at early times of pumping tests than at later times (e.g., Wu et al. 2005; Bohling 2009).

Comparison and Detection Limits

Figure 4c shows a comparison of drawdown data, recorded by both a FO transducer and a strain-gauge (non-FO) transducer in each of two observation zones, illustrating the good agreement of drawdown measurements for both transducer types—after initiation of drawdown is detected by a given transducer. That is, it shows the difference in detection limits such that important small-drawdown data may be missed due to the limited

ability of common types of non-FO transducers to resolve drawdowns smaller than 3 to 5 mm. To help illustrate this point further, the horizontal green line in Figure 4 marks a 3 mm resolution or detection limit typical of some commonly used non-FO pressure transducers. This would be especially critical for the response shown in Figure 4b for which important low-drawdown behavior would not be recorded at all. But also important “early-time” drawdown prior to exceeding the detection limit (Figure 4a) has hydrologic meaning for K , and especially S_s , that would be missed.

For additional context, we note two examples from recent literature on advanced testing methods (3D hydraulic tomography and multiwell hydromechanical testing) where authors stated and showed transducer detection limits that may have reduced their ability to record important low-drawdown responses (e.g., compare with Figure 4b). Berg and Illman (2011) note promising hydraulic tomography results in the highly heterogeneous aquifer at the NCRS (North Campus Research Site at the University of Waterloo, Canada), but also that “drawdown responses need to be monitored at higher resolutions to obtain finer scale detail in heterogeneity.” Their non-FO transducers and data plots for this study and a follow-up study (Zhao and Illman 2018) indicate detection limits of about 3 to 5 mm. Earnest et al. (2019) present a field and modeling study advancing hydromechanical testing in a fractured aquifer to include multiple observation wells. They identify the resolution limit of their non-FO transducers to be 3 mm and show data plots suggesting that the ability to detect responses less than 3 mm might capture behavior of interest at otherwise marginally responding or nondetecting locations.

Testing Duration and Drift

A current limitation for aquifer testing with FO transducers is the possibility of long-term signal drift which has been observed for tests longer than several hours. In our experience, small drifts in pressure signals after several hours had different trends for different transducers and could not be attributed to changes in the hydraulic aquifer response or atmospheric pressure, but may be caused by drifts of individual transducers or the data acquisition system. However, such drifting was not observed during our field tests with durations of less than 2 h.

Discussion of New Experimental Opportunities

Above we show that FO transducers meet or exceed capabilities of commonly used non-FO transducers for high-resolution, fast head-change measurements, and also have useful logistical features for hydrologic testing (lasting several hours or less), and especially for testing with many transducers which enable high-resolution 3D investigations. In this section, we first briefly highlight some applications using FO systems in emerging testing methods that suggest some new possibilities associated with resolving 3D heterogeneity in unconsolidated sedimentary and fractured aquifers. Then we note additional

experimental possibilities, some of which might benefit from longer term FO transducer stability and/or greater separation distances between observation locations than are currently feasible.

FO Transducers and Emerging Testing Methods

A major motivation for research and development in hydrologic testing is to accurately quantify (i.e., approach “actual”) heterogeneity of aquifer parameters and structure at high-resolution for field scales of 10s of meters in three dimensions—e.g., to achieve successful source-zone remediation of groundwater contamination. Such scales are smaller than the REV for many highly heterogeneous aquifers in sediments and fractured rock, and prior geostatistical, geologic, hydrogeologic, and geophysical information commonly includes uncertainties and/or errors that can bias high-resolution, 3D, distributed, parameter estimations. Hydraulic tomography is an emerging testing method for estimating 3D heterogeneous aquifer properties with general applicability beyond contaminant hydrology. Here we note several proof-of-concept 3D-hydraulic tomography studies enabled by the logistically friendly use of up to 35 FO transducers for high-resolution drawdown observations (i.e., from numerous zones of wells during numerous pumping tests) that are input to data-driven tomographic inversion. Results and operational experience from such studies suggest new experimental possibilities by using FO transducers in areas of long-standing research in the field of subsurface hydrology, new areas of interest (e.g., critical zone investigations), and for new hydraulic tomography methods (e.g., Klepikova et al. 2013; Paradis et al. 2016; Cardiff et al. 2020). In this regard, non-FO transducers with similar resolution capabilities as FO transducers would also be suitable for such new possibilities, under alternative logistical configurations to those for FO transducers.

Topic 1: 3D Aquifer Heterogeneity in Unconsolidated Sediments

Hochstetler et al. (2016) used 3D hydraulic tomography with drawdown data from up to 35 FO transducers during 26 pumping tests to estimate the 3D hydraulic conductivity distribution at high resolution (with minimal assumptions or priors) as distributed parameters in a highly heterogeneous unconfined aquifer of clay to sand and gravel lenses (K range of almost seven orders of magnitude). The hydraulic tomography identified continuity and discontinuity of lenses in locations not predictable by projecting core lithologies between adjacent CMT wells (e.g., Figure 4 in Hochstetler et al. 2016).

Interest in and development of research field sites to improve subsurface imaging and characterization methods and models has grown over the last 20+ years (National Research Council 2000; Rubin and Hubbard 2005; Anderson and McCray 2011). Now significant infrastructure and data sets are available at a number of sites. These developments suggest new possibilities with use of FO transducers for upgrading to near-actual high-resolution 3D aquifer-parameter distributions and for testing to advance the

long-standing goals of: (1) finding petrophysical relations and calibrating indirect geophysical methods against fully 3D high-quality, high-resolution aquifer-parameter distributions; and (2) quantitatively assessing test design for efficiency and data worth to achieve desired resolution of 3D K heterogeneity—both with and without the use of prior data, spatial structure models, and/or one or several geophysical methods.

Topic 2: 3D Aquifer Heterogeneity in Fractured Rock

Tiedeman and Barrash (2020) conducted high-resolution distributed-parameter 3D hydraulic tomography in a fractured aquifer using ~32 FO transducers and 14 strain-gauge transducers (with minimal assumptions or priors). The results explained heterogeneous behavior associated with major fractures and a cross-cutting low-K feature, and with the rest of the fracture network via lower K connecting fractures that could be mapped by tracing drawdown pathways through the tested volume, and that showed the connectivity routes through the fracture network for different pumping locations and rates.

Follow-up possibilities include testing with FO transducers to achieve closer approximations to actual in situ fracture shapes and orientations, and to test theories and models of fracture-network structure—including discrete fracture network models, statistics/geostatistics, hydromechanical behavior (see below), and flow and transport behavior.

Topic 3: Combining Hydraulic Tomography with Tracer Tests for Improved Flow and Transport Models

Sánchez-León et al. (2020) combined 3D hydraulic tomography with 3D tracer tomography in an unconsolidated gravel aquifer to estimate 3D representations of the means and variances of hydraulic conductivity using Ensemble Kalman Filtering. For the generation of the combined hydraulic and tracer data set, they placed both FO transducers and FO fluorescence sensors along with small-diameter tracer sampling tubing together in the same CMT monitoring zones, that is, multiple sensors and tubing in single observation intervals, which would not be possible with non-FO transducers.

These developments suggest new possibilities with the use of FO transducers for the simultaneous collection of head and transport data for improved test designs and to advance 3D flow and transport modeling. For example, such an approach can advance the use of partitioning tracer tests (Yeh and Zhu 2007) for the difficult and important case of locating and then targeting residual DNAPLs, for example, in fracture networks (Schaefer et al. 2016) with “surgical” in situ remediation (Leeson et al. 2013) based on data-driven models rather than generalized or assumed fractured-aquifer structure and behavior.

Topic 4: Hydromechanical Testing for Properties and First-Principles Fracture Flow Behavior

Recent field tests and modeling have related fracture deformations and aquifer permeability changes

with pressure in slug and pumping tests (Schweisinger et al. 2009, 2011), and now are examining behavior between wells but being limited perhaps by resolution of transducers used (Earnest et al. 2019). These developments suggest new possibilities with use of FO transducers for improved resolution and greater density of observations for advancing first-principles fracture flow dynamics, with engineering rock-structural implications and flow and transport implications, and could be combined with 3D fracture network maps from hydraulic tomography as noted above.

Recommendations for FO Transducer System Improvements to Expand Testing Possibilities

Further developments of FO systems should target (1) eliminating the long-term drift to allow long-term pressure-change measurements, and (2) enabling distributed transducer/signal conditioner operation with wireless control that can be deployed at relatively distant locations. Such improvements would not only expand the time and size scales of testing methods noted above, but would enable broader applications to engineering and infrastructure (nuclear waste repositories, mines, dams, tunnels, CO₂ sequestration, fracking, geothermal, ...) such as pressure pulse testing for CO₂ leakage detection and monitoring at CCS sites (e.g., Shakiba and Hosseini 2016; Tran and Zeidouni 2018; Hosseini 2019) or in the context of hydromechanical characterization and including (deep) underground structures such as geological repositories (e.g., Beauheim et al. 2014; Bishop et al. 2020; Brixel et al. 2020), and excavation damaged zones (e.g., Bossart et al. 2002; Marschall et al. 2017), or geothermal systems (e.g., Borello et al. 2019; Fan et al. 2020; Kittila et al. 2020).

Summary

In this Method Note, we discuss the current state of FPI-based FO pressure measurements with a special focus on measurement aspects including advantages and limitations of this technique for hydrogeological applications. In this context, the FO system is especially well-suited for use in short-term hydraulic experiments (with test durations in the range of seconds, such as for fast-response slug tests, up to a few hours) during which drift of the FO system is negligible in comparison to head changes of the test itself. Based on field test examples, we show that the FO system produces dependable data with higher resolution than many commonly used transducers, and generally better than ranges specified by the FO manufacturer.

Due to the small-diameter design of the FO transducers it is possible to use the system in combination with small-diameter tubing, sampling points, and multi-level wells and multichannel tubing as well as with Direct Push-based installations. Threading the transducers into tubing is fast and easy, and does not require pressure-tight seals at individual zones of multizone packed-off systems. Our investigations further showed reliable field

performance of FO pressure systems with high data consistency between FO transducers, and resolution of 1 mm and less achieved by selecting small full-scale ranges of pressure (as the FO transducers can be placed just below the expected drawdown of water level in guiding or measuring tubes acting as miniaturized piezometers), and by further noise reduction with data averaging or smoothing.

In summary, FO pressure transducer systems are a valuable tool for reliable measurement of groundwater level changes with very high temporal and spatial resolution, advantageous logistical features, and moderate costs. Given the above, FO transducers offer another option for conventional hydrologic testing and can open new experimental possibilities in areas such as: high-resolution 3D heterogeneity (flow and transport, remediation, critical zones); 3D fracture networks and fundamental hydromechanical behavior; and complex 3D flow and leak detection (mines, dams, repositories, geothermal systems).

Acknowledgments

We thank the Editor-in-Chief Leonard F. Konikow, the Executive Editor Yu-Feng Lin, the reviewers Jim Butler and Jui-Pin Tsai as well as two anonymous reviewers for their constructive comments and suggestions, which significantly improved this article. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the authors. Open Access funding enabled and organized by Projekt DEAL.

Authors' Note

The authors do not have any conflicts of interest or financial disclosures to report.

References

- Anderson, M.P., and J. McCray. 2011. Foreword: Lessons learned about contaminant hydrogeology from legacy research sites. *Groundwater* 49, no. 5: 617–619.
- Ball, D.W. 2006. *Field Guide to Spectroscopy*. Bellingham, Washington: SPIE Press.
- Bao, X.Y., and L. Chen. 2012. Recent progress in distributed fiber optic sensors. *Sensors* 12, no. 7: 8601–8639.
- Barrash, W., and T. Clemo. 2002. Hierarchical geostatistics and multifacies systems: Boise Hydrogeophysical Research Site, Boise, Idaho. *Water Resources Research* 38, no. 10: 1196.
- Beach, R.A., R.W. Sternberg, and R. Johnson. 1992. A fiber optic sensor for monitoring suspended sediment. *Marine Geology* 103, no. 1-3: 513–520.
- Beauheim, R.L., R.M. Roberts, and J.D. Avis. 2014. Hydraulic testing of low-permeability Silurian and Ordovician strata, Michigan Basin, southwestern Ontario. *Journal of Hydrology* 509: 163–178.
- Becker, M.W., B. Bauer, and A. Hutchinson. 2013. Measuring artificial recharge with fiber optic distributed temperature sensing. *Groundwater* 51, no. 5: 670–678.
- Benitez-Buelga, J., C. Sayde, L. Rodriguez-Sinobas, and J.S. Selker. 2014. Heated fiber optic distributed temperature sensing: A dual-probe heat-pulse approach. *Vadose Zone Journal* 13, no. 11.

- Berg, S.J., and W.A. Illman. 2011. Three-dimensional transient hydraulic tomography in a highly heterogeneous glaciofluvial aquifer-aquitard system. *Water Resources Research* 47: W10507.
- Bishop, P., E. Persaud, J. Levison, B. Parker, and K. Novakowski. 2020. Inferring flow pathways between bedrock boreholes using the hydraulic response to borehole liner installation. *Journal of Hydrology* 580: 124267.
- Bohling, G.C. 2009. Sensitivity and resolution of tomographic pumping tests in an alluvial aquifer. *Water Resources Research* 45, no. 2: W02420.
- Borello, E.S., P.A. Fokker, D. Viberti, F. Verga, H. Hofmann, P. Meier, K.B. Min, K. Yoon, and G. Zimmermann. 2019. Harmonic pulse testing for well monitoring: Application to a fractured geothermal reservoir. *Water Resources Research* 55, no. 6: 4727–4744.
- Bossart, P., P.M. Meier, A. Moeri, T. Trick, and J.C. Mayor. 2002. Geological and hydraulic characterisation of the excavation disturbed zone in the Opalinus Clay of the Mont Terri Rock Laboratory. *Engineering Geology* 66, no. 1–2: 19–38.
- Brixel, B., M. Klepikova, M.R. Jalali, Q. Lei, C. Roques, H. Kriestch, and S. Loew. 2020. Tracking fluid flow in shallow crustal fault zones: 1. Insights from single-hole permeability estimates. *Journal of Geophysical Research-Solid Earth* 125: 4.
- Buerck, J., S. Roth, K. Kraemer, M. Scholz, and N. Klaas. 2001. Application of a fiber-optic NIR-EFA sensor system for in situ monitoring of aromatic hydrocarbons in contaminated groundwater. *Journal of Hazardous Materials* 83, no. 1–2: 11–28.
- Butler, J.J., and X.Y. Zhan. 2004. Hydraulic tests in highly permeable aquifers. *Water Resources Research* 40: 12.
- Butler, J.J., C.D. McElwee, and G.C. Bohling. 1999. Pumping tests in networks of multilevel sampling wells: Motivation and methodology. *Water Resources Research* 35, no. 11: 3553–3560.
- Cardiff, M., Y.Q. Zhou, W. Barrash, and P.K. Kitanidis. 2020. Aquifer imaging with oscillatory hydraulic tomography: Application at the field scale. *Groundwater* 58, no. 5: 710–722.
- Cardiff, M., W. Barrash, and P.K. Kitanidis. 2013. Hydraulic conductivity imaging from 3-D transient hydraulic tomography at several pumping/observation densities. *Water Resources Research* 49, no. 11: 7311–7326.
- Cardiff, M., W. Barrash, and P.K. Kitanidis. 2012. A field proof-of-concept of aquifer imaging using 3-D transient hydraulic tomography with modular, temporarily-emplaced equipment. *Water Resources Research* 48, no. 5: W05531.
- Dietrich, P., and C. Leven. 2006. Direct push-technologies. In *Groundwater Geophysics. A Tool for Hydrogeology*, ed. R. Kirsch, 321–340. Berlin: Springer.
- Dyer, S.A. 2004. *Wiley Survey of Instrumentation and Measurement*. New York: John Wiley & Sons.
- Earnest, E., D. Boutt, L. Murdoch, and W.P. Clement. 2019. Static and dynamic conceptual model of a complexly fractured crystalline rock aquifer. *Hydrological Processes* 33, no. 20: 2691–2710.
- Einarson, M.D., and J.A. Cherry. 2002. A new multilevel ground water monitoring system using multichannel tubing. *Groundwater Monitoring and Remediation* 22, no. 4: 52–65.
- Fan, Z., R. Parashar, and Z.-H. Jin. 2020. Impact of convective cooling on pore pressure and stresses around a borehole subjected to a constant flux: Implications for hydraulic tests in an enhanced geothermal system reservoir. *Interpretation—A Journal of Subsurface Characterization* 8, no. 2: SG13–SG20.
- Halloran, L.J.S., H. Roshan, G.C. Rau, M.S. Andersen, and R.I. Acworth. 2016. Improved spatial delineation of streambed properties and water fluxes using distributed temperature sensing. *Hydrological Processes* 30, no. 15: 2686–2702.
- Hochstetler, D.L., W. Barrash, C. Leven, M. Cardiff, F. Chidichimo, and P.K. Kitanidis. 2016. Hydraulic tomography: Continuity and discontinuity of high-K and low-K zones. *Groundwater* 54, no. 2: 171–185.
- Hosseini, S.A. 2019. Fault leakage detection and characterization using pressure transient analysis. *Journal of Petroleum Science and Engineering* 176: 880–886.
- Kipp, K.L. 1985. Type curve analysis of inertial effects in the response of a well to a slug test. *Water Resources Research* 21, no. 9: 1397–1408.
- Kittila, A., M.R. Jalali, M. Somogyvari, K.F. Evans, M.O. Saar, and X.Z. Kong. 2020. Characterization of the effects of hydraulic stimulation with tracer-based temporal moment analysis and tomographic inversion. *Geothermics*: 86.
- Klepikova, M.V., T. Le Borgne, O. Bour, and J.R. de Dreuzy. 2013. Inverse modeling of flow tomography experiments in fractured media. *Water Resources Research* 49, no. 11: 7255–7265.
- Leeson, A., H.F. Stroo, and P.C. Johnson. 2013. Groundwater remediation today and challenges and opportunities for the future. *Groundwater* 51, no. 2: 175–179.
- Lessoff, S.C., U. Schneidewind, C. Leven, P. Blum, P. Dietrich, and G. Dagan. 2010. Spatial characterization of the hydraulic conductivity using direct-push injection logging. *Water Resources Research* 46(12), W12502.
- Leven, C., H. Weiss, T. Vienken, and P. Dietrich. 2011. Direct push technologies—An efficient investigation method for subsurface characterization. *Groundwater* 16, no. 4: 221–234.
- Marschall, P., S. Giger, R. De la Vassiere, H. Shao, H. Leung, C. Nussbaum, T. Trick, B. Lanyon, R. Senger, A. Lisjak, and A. Alcolea. 2017. Hydro-mechanical evolution of the EDZ as transport path for radionuclides and gas: Insights from the Mont Terri rock laboratory (Switzerland). *Swiss Journal of Geosciences* 110, no. 1: 173–194.
- National Research Council (NRC). 2000. *Research Needs in Subsurface Science*. Washington, DC: National Research Council, National Academies Press.
- Paradis, D., E. Gloaguen, R. Lefebvre, and B. Giroux. 2016. A field proof-of-concept of tomographic slug tests in an anisotropic littoral aquifer. *Journal of Hydrology* 536: 61–73.
- Roriz, P., O. Frazao, A.B. Lobo-Ribeiro, J.L. Santos, and J.A. Simoes. 2013. Review of fiber-optic pressure sensors for biomedical and biomechanical applications. *Journal of Biomedical Optics* 18, no. 5: 50903.
- Rubin, Y., and S.S. Hubbard. 2005. Hydrogeophysics. In *Water Science and Technology Library*, Vol. 8, ed. V.P. Singh, 521. Dordrecht: Springer.
- Sánchez-León, E., C. Leven, D. Erdal, and O.A. Cirpka. 2020. Comparison of two ensemble-Kalman filter based methods for estimating aquifer parameters from real 3-D hydraulic and tracer tomographic tests. *Geosciences* 10: 462.
- Sanchez-León, E.E. 2018. Solute tracer tomography: Field implementation and parameter estimation using the ensemble Kalman filter. PhD Thesis, Faculty of Science, University of Tübingen, Tübingen.
- Sanchez-León, E., C. Leven, C.P. Haslauer, and O.A. Cirpka. 2016. Combining 3D hydraulic tomography with tracer tests for improved transport characterization. *Groundwater* 54, no. 4: 498–507.
- Sayde, C., C. Gregory, M. Gil-Rodríguez, N. Tuffillaro, S. Tyler, N. van de Giesen, M. English, R. Cuenca, and J.S. Selker. 2010. Feasibility of soil moisture monitoring with heated fiber optics. *Water Resources Research*: 46(6).
- Schaefer, C.E., E.B. White, G.M. Lavorgna, and M.D. Annable. 2016. Dense nonaqueous-phase liquid architecture in fractured bedrock: Implications for treatment and plume

- longevity. *Environmental Science & Technology* 50, no. 1: 207–213.
- Schweisinger, T., E.J. Svenson, and L.C. Murdoch. 2011. Hydromechanical behavior during constant-rate pumping tests in fractured gneiss. *Hydrogeology Journal* 19, no. 5: 963–980.
- Schweisinger, T., E.J. Svenson, and L.C. Murdoch. 2009. Introduction to Hydromechanical well tests in fractured rock aquifers. *Groundwater* 47, no. 1: 69–79.
- Sebok, E., C. Duque, P. Engesgaard, and E. Boegh. 2015. Application of distributed temperature sensing for coupled mapping of sedimentation processes and spatio-temporal variability of groundwater discharge in soft-bedded streams. *Hydrological Processes* 29, no. 15: 3408–3422.
- Shakiba, M., and S.A. Hosseini. 2016. Detection and characterization of CO₂ leakage by multi-well pulse testing and diffusivity tomography maps. *International Journal of Greenhouse Gas Control* 54: 15–28.
- Sorensen, J.P.R., and A.S. Butcher. 2011. Water level monitoring pressure transducers—A need for industry-wide standards. *Groundwater Monitoring and Remediation* 31, no. 4: 56–62.
- Tamari, S., and A. Aguilar-Chavez. 2010. Testing submersible pressure transducers to monitor water level in tanks. *Tecnologia Y Ciencias Del Agua* 1, no. 3: 71–88.
- Tiedeman, C.R., and W. Barrash. 2020. Hydraulic tomography: 3D hydraulic conductivity, fracture network, and connectivity in mudstone. *Groundwater* 58, no. 2: 238–257.
- Tiedeman, C.R., W. Barrash, C. Thrash, and J. Patterson. 2019. Pumping rate, drawdown, and atmospheric pressure data from hydraulic tomography experiment at the former Naval Air Warfare Center, West Trenton, NJ, 2015-2016 [Data set]. U.S. Geological Survey. <https://doi.org/10.5066/P95XFIYV>
- Tiedeman, C.R., P.J. Lacombe, and D.J. Goode. 2010. Multiple well-shutdown tests and site-scale flow simulation in fractured rocks. *Groundwater* 48, no. 3: 401–415.
- Tolansky, S. 1973. *An Introduction to Interferometry*. London: Longmans, Green and Co.
- Totsu, K., Y. Haga, and M. Esashi. 2005. Ultra-miniature fiber-optic pressure sensor using white light interferometry. *Journal of Micromechanics and Microengineering* 15, no. 1: 71–75.
- Tran, N., and M. Zeidouni. 2018. Pressure transient technique to constrain CO₂ plume boundaries. *Environmental Earth Sciences* 77, no. 21, 736.
- Udd, E., and W.B. Spillman. 2011. *Fiber Optic Sensors: An Introduction for Engineers and Scientists*. Chichester: Wiley.
- Westhoff, M.C., H.H.G. Savenije, W.M.J. Luxemburg, G.S. Stelling, N.C. van de Giesen, J.S. Selker, L. Pfister, and S. Uhlenbrook. 2007. A distributed stream temperature model using high resolution temperature observations. *Hydrology and Earth System Sciences* 11, no. 4: 1469–1480.
- Wu, C.M., T.C.J. Yeh, J.F. Zhu, T.H. Lee, N.S. Hsu, C.H. Chen, and A.F. Sancho. 2005. Traditional analysis of comparing apples to oranges? *Water Resources Research* 41, no. 9, W09402.
- Yeh, T.-C.J., and J. Zhu. 2007. Hydraulic/partitioning tracer tomography for characterization of dense nonaqueous phase liquid source zones. *Water Resources Research* 43, no. 6, W06435.
- Yeo, T.L., T. Sun, and K.T.V. Grattan. 2008. Fibre-optic sensor technologies for humidity and moisture measurement. *Sensors and Actuators A—Physical* 144, no. 2: 280–295.
- Yin, S., P.B. Ruffin, and F.T.S. Yu. 2008. *Fiber Optic Sensors*. Boca Raton, Florida: CRC Press.
- Yu, Q., and X. Zhou. 2011. Pressure sensor based on the fiber-optic extrinsic Fabry-Perot interferometer. *Photonic Sensors* 1, no. 1: 72–83.
- Zhang, Y., X. Lei, T. Hashimoto, and Z. Xue. 2021. Toward retrieving distributed aquifer hydraulic parameters from distributed strain sensing. *Journal of Geophysical Research: Solid Earth* 126, no. 1: e2020JB020056.
- Zhao, Z.F., and W.A. Illman. 2018. Three-dimensional imaging of aquifer and aquitard heterogeneity via transient hydraulic tomography at a highly heterogeneous field site. *Journal of Hydrology* 559: 392–410.