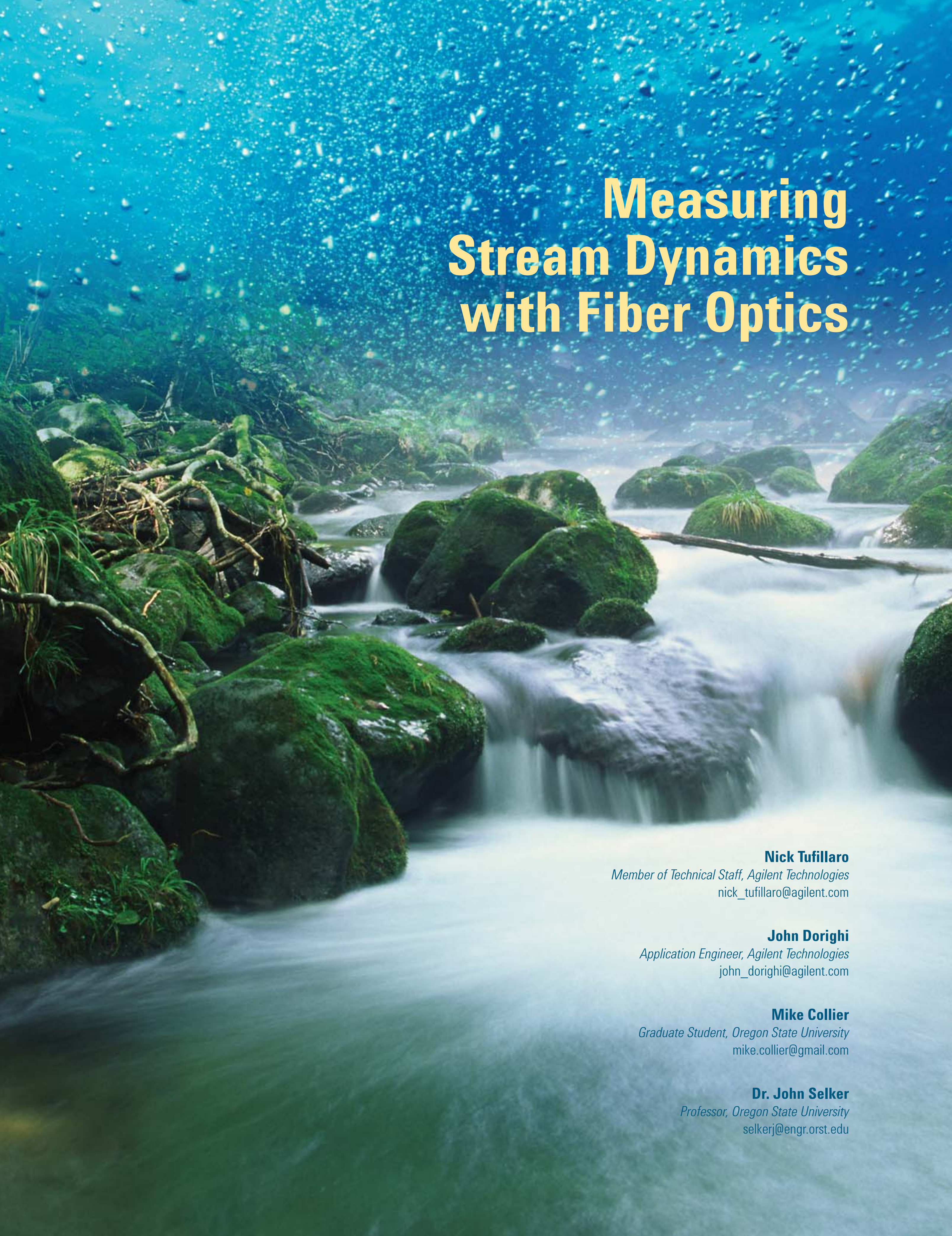

Measuring Stream Dynamics with Fiber Optics

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Climate change is a story that begins with temperature and often ends with water — melting glaciers, rising sea levels, storms and regional stresses on freshwater sources. Remote sensing from satellites provides the big picture, but a regional understanding of the impact of environmental change requires detailed measurements on the ground. One key measurement of a regional environment is “streamflow,” which hydrologists define as the movement of water in a natural channel.

Lakes and rainwater runoff are obvious places to start when looking for sources of streamflows. However, most of the available freshwater exists not on the surface but in the ground, and underwater springs, which are a significant contributor to streamflow, are currently not well measured or modeled. Locating and gauging these groundwater inputs requires measurements able to cover several kilometers with resolution as fine as one meter. Traditional “point measurement” instruments used in hydrology cannot handle this challenge; however, new distributed measurement technologies that use fiber optic temperature sensors can provide the required reach and resolution.

These sensors quickly measure temperature over a few kilometers with resolution down to a meter, and this temperature data can be used to uncover the groundwater interactions with stream water. However, instruments developed for *in situ* environmental measurements must also be field deployable, energy efficient (typically operating from batteries or solar cells) and pest-proof.

The Agilent N4386A distributed temperature system (DTS) uses fiber optics to meet these measurement challenges. The DTS is used in a wide range of applications: downhole oil and gas reservoir performance monitoring; power cable monitoring; pipeline and water dam leakage detection; and in security applications such as fire detection in tunnels, refineries or other special-hazard applications. Geophysical scientists are also using this instrument to address a variety of hydrological applications. This article highlights one such project, done in collaboration with Oregon State University, Corvallis, Oregon to measure the connection between surface streamflows and subsurface water sources.

Basics of DTS operation

The DTS uses light to measure temperature. It starts each measurement by launching a pulse of light from a semiconductor laser into a standard communications optical fiber and then measuring the backscattered light to first determine time-of-flight and then position.

Three important scattering mechanisms are present in an optical fiber: Rayleigh, Brillouin and Raman. The Agilent DTS uses the spontaneous Raman scattering signal and measures changes in the intensity at the Stokes line, which is temperature-dependent, and the Anti-Stokes line, which is mostly temperature independent. The temperature is then computed from the ratio of these two lines after performing a fiber-dependent calibration procedure. The basic relation is written as

$$\frac{I_{AS}}{I_S} \propto \exp\left(\frac{h\Delta\nu_R}{kT}\right)$$

where h is the Planck constant, k is the Boltzmann constant, T is the absolute temperature and $\Delta\nu_R$ is the separation between Raman Anti-Stokes/Stokes and probe-light frequencies.

In the DTS, temperature resolution varies with distance, spatial resolution and temporal averaging. A total of 8000 measurement points can be acquired during every averaging period. This allows spatial resolution down to 1.5 m for measurement spans of up to 12 km and down to 1 m for distances up to 8 km. For example, a temperature resolution of 0.11° C is possible at a distance of 2 km (1.5 m spatial resolution) with 10 minutes of temporal averaging. Reducing the temporal averaging to thirty seconds decreases the temperature precision to 0.35° C.

During set up and calibration in the field, temperature accuracy (along with precision) is typically checked with a few independent single-point temperature measurements. A two- or four-channel DTS offers additional capability for dual-ended or loop-back measurements. The ongoing auto-calibration present in a dual-ended measurement further simplifies the calibration and improves measurement accuracy.

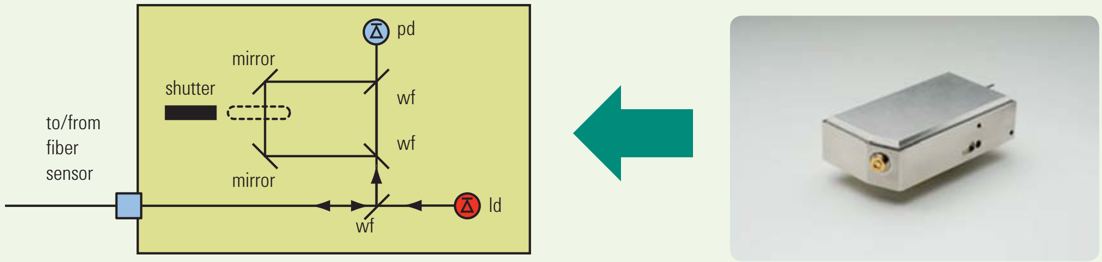


Figure 1. The integrated optical assembly in the Agilent DTS includes a low-power semiconductor laser (ld) and a single-receiver optical detector (pd). The concept uses a series of wavelength filters (wf) and mirrors direct the backscattered Stokes and Anti-Stokes lines from the fiber sensor to the photo diode. (Figure adapted from Reference 1.)

Looking inside the Agilent DTS

The core of the Agilent DTS is an integrated optical block that contains a laser source, filters and a single optical detector in a bulk optical assembly. The entire assembly is hermetically sealed and filled with an inert gas, isolating the components and preventing condensation from degrading instrument performance over its range of operating temperatures. A schematic of the optical assembly is shown in Figure 1. Two unique aspects of the design are its use of a low-power semiconductor laser and its single-receiver optical detector.

The DTS uses a low-power external-cavity diode laser operating at 1064 nm. A semiconductor laser ensures a long operating life, eliminating the need for field-replaceable parts. This is an important requirement for reliable, maintenance-free measurements in remote locations. Additionally, the average optical power from the source is ~17 mW, which classifies the laser as a Class 1M "eye safe" device — unlike other commercial instruments that use solid state YAG lasers.

The optical path for the single-receiver design is also shown in Figure 1. Light from the source is coupled into the sensing fiber and backscattered light is directed toward the detector through a series of filters and reflectors. The Agilent DTS measures both the Anti-Stokes (1018 nm) and Stokes (1112 nm) lines using a single optical receiver. A single receiver improves the instrument's measurement accuracy over a wide range of operating temperature by eliminating drift, which can occur in dual-receiver designs. The apparent change in temperature reported by the DTS is less than 1° C as the ambient operating temperature of the DTS changes over its entire 70° C range.

The choice of a power-efficient semiconductor laser carries a technical challenge: the resulting backscattered light has limited signal strength at the receiver, and this translates into a lower signal-to-noise ratio. Agilent engineers overcame this issue using a code-correlation technique to boost signal level and improve the signal-to-noise ratio, making it comparable to higher-power, single-pulse laser sources.[2] This approach was leveraged from Agilent's 20 years of experience designing and manufacturing rugged, field-reliable optical time-domain reflectometers (OTDRs) and external-cavity diode lasers.

Making it field-ready

To address rugged, outdoor field applications, the Agilent DTS is designed around an integrated optical block. The instrument also includes an IP66 (NEMA 4) enclosure to prevent moisture from interfering with instrument operation (Figure 2). Additionally, the optical block is temperature stabilized, allowing operation from –10° C to +60° C. Operation at lower temperatures is made possible by adding insulation that traps heat generated by the instrument: With this extra warmth, the DTS will continue to function even if the external temperature drops below –10° C. In a trial, the DTS operated down to –40° C using only external insulation with no internal heating elements. The instrument can be operated with standard telecom fibers for normal temperature ranges or with special fibers that cover a temperature span of –273° C to +700° C, depending on sensor coating.

Figure 2. An IP66/NEMA4 enclosure prevents moisture from interfering with instrument operation.

In remote deployments, power consumption is a critical factor. The DTS offers a nominal power consumption of 15 W (< 40 W peak) and can use DC sources such as batteries and solar panels.

Measuring the water cycle

The water cycle begins with the sun heating the oceans and lifting moisture to the clouds. Precipitation falls to the Earth and starts its journey back toward the sea, driven by gravity. Water on the Earth's surface is easily seen in rainwater runoff to lakes, rivers and streams. Less visible is the water below the ground. Groundwater makes up 98 percent of available fresh water and its importance can not be underestimated: It supplies 40 percent of the fresh water in the United States and 70 percent in China.[3, 4] In addition to human uses, groundwater is essential as a freshwater source for springs, rivers, lakes and their surrounding habitats. Despite its critical role in the water cycle, the interaction of surface water and groundwater is difficult to measure and therefore difficult to understand, model and manage.

Getting a local look at the water cycle typically involves the use of hydrologic tracers. A variety of passive (O16/O18, tritium, CFCs) and active (dyes) tracers allow hydrologists to piece together a detailed picture of the path taken by water both above and below the ground. For instance, measurements of O16/O18 ratios allow the determination of "residence time," which is the average time the water spends in a given reservoir. These measurements often provide the key data needed to determine the origin and subsequent path water takes during its extended journey underground.[5]

Heat can also be used as a tracer. Because the temperatures of streams and subsurface springs differ, temperature measurements can provide a distributed, real-time look at the interaction of stream waters and their surrounding groundwater aquifers.

Examining stream dynamics with the DTS

New distributed temperature-sensing applications in hydrology are being developed at Oregon State University. Examples include measuring flow patterns in lakes via temperature, upwelling of water-borne pollutants in abandoned mine shafts, and the thermal interactions of air and snow.[6]

For temperature-based measurements of flow patterns, environmentally rugged — but otherwise standard — communications optical fibers are placed in streams as shown in Figure 3. The distributed temperature sensor locates groundwater sources by looking for steps in the temperature change indicative of groundwater influx. Several different methods, all based on conservation of energy and mass, enable not only the determination of the location of groundwater inputs but also quantitative estimates of the groundwater inputs to streamflow. One such method starts with measurements of temperatures upstream and downstream from the groundwater source. Coupling this information with knowledge of the groundwater temperature enables estimates of changes in the flow rate using the following relation:

$$Q_0 = Q_i \left(\frac{T_g - T_i}{T_g - T_o} \right)$$

In this equation, Q_o is the streamflow after the groundwater source (usually reported in cubic feet per second), Q_i is the streamflow before the groundwater source, T_g is the groundwater temperature, T_i is the temperature before the groundwater source, and T_o is the temperature after the groundwater source.[7]

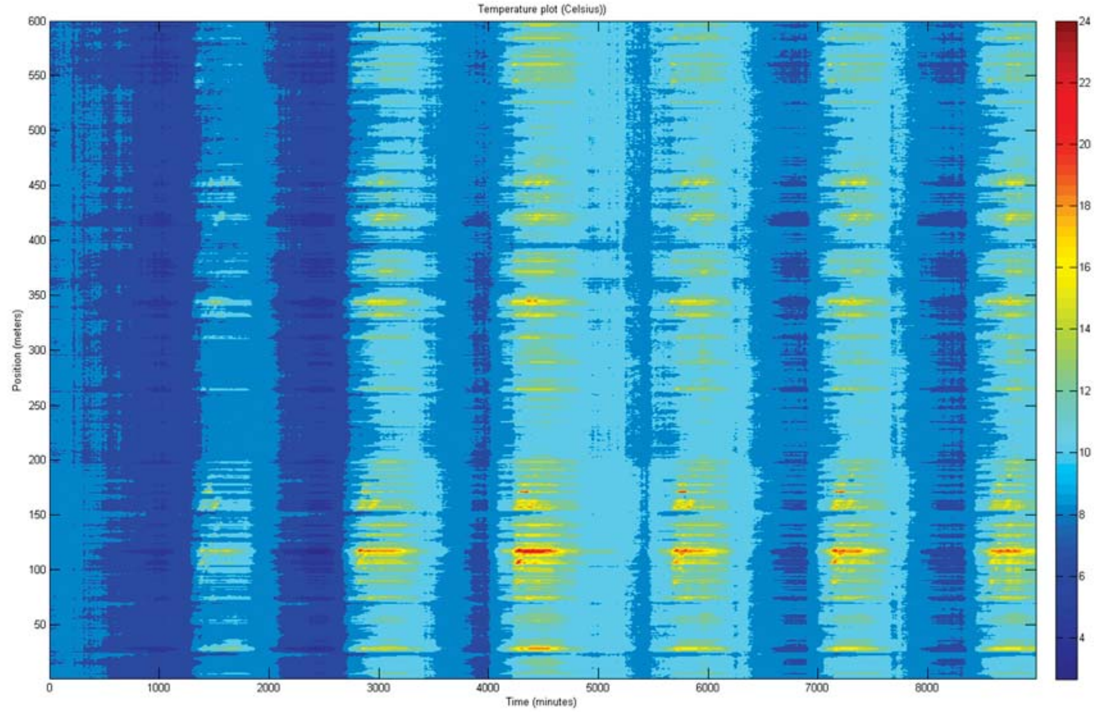
During the spring of 2007, an Agilent N4386A DTS was installed at watershed one of the H.J. Andrews Experimental Forest in the Cascade Mountain Range of western Oregon. The forest is one of the National Science Foundation's long-term ecological research sites (NSF-LTER). One goal of the Andrews LTER studies is to understand how land use, natural disturbances and climate change affect key ecosystem properties such as carbon dynamics, biodiversity and hydrology.

The site is heavily instrumented and is used, for instance, to study effects of land use and climate change on essential environmental properties supporting ecosystems.[8] The DTS installation includes one kilometer of rugged optical fiber with the last 600 meters installed in the stream. Metal ties secure the fiber along the stream bed. The instrumentation is powered using a bank of 12-V batteries.

Measurement results from the Andrews installation are shown in Figure 4, which reveals variations in the stream temperature and surrounding air over one week. This particular data set clearly illustrates how the local air temperature drives shallow-water stream temperatures.

In addition to its use for hydrological science, the installation is also used for training. During the fall of 2007, the Andrews installation will be the site of a workshop called "Fiber Optic Distributed Temperature Sensing for Ecological Characterization." Staff from Oregon State University and the U.S. Geological Survey (USGS) will lead the workshop.[9]

Figure 3. Installing fiber at the H. J. Andrews Experimental Forest in the western Cascade Range of Oregon.



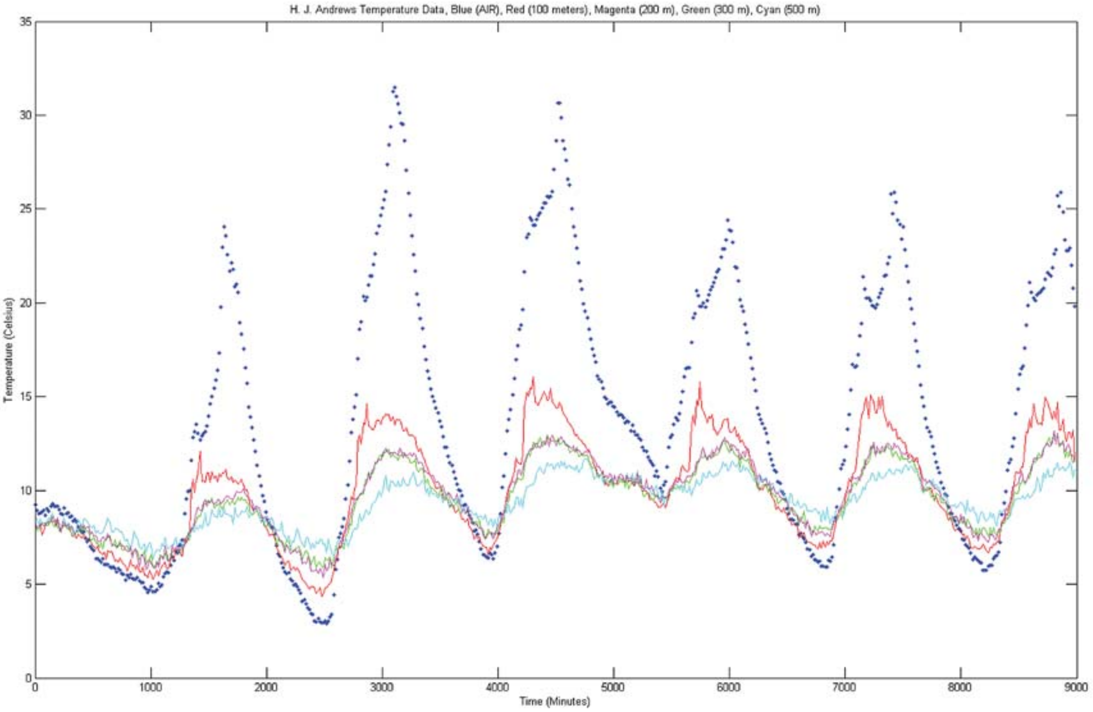


Figure 4. Temperature records from the Andrews installation at watershed one, May 12-19, 2007. Major oscillations are from diurnal cycle. The lower graph shows stream temperature at three positions; the dots show out-of-stream air temperatures also measured by the DTS system.

A second installation was deployed during the summer of 2007 in the Walla Walla region of southeastern Washington State. Walla Walla (literally "water, water" in the Native American Sahaptin language) is a rich agricultural area famous for sweet onions, winter wheat and, more recently, wine. The Walla Walla Basin Watershed Council is overseeing a number of hydrological monitoring projects, including a recharge project that takes a significant portion the Walla Walla River and directs it back into regional aquifers.[10] Over the past 50 years, groundwater pump-down caused many streams to disappear, taking with them the fish and wildlife that depended on those streams. The Agilent DTS is aiding in both gauging the recharge of the aquifers and providing a first-hand look at the streams that are returning to the Walla Walla region after a 50-year absence.

Conclusion

Streamflow dynamics are the lifeblood of many ecological communities. Distributed temperature sensing is a unique new technology researchers can use to better measure and understand environments and ecologies. The technology opens new possibilities for assessing water quantity and quality in real-time with excellent resolution in both space and time. Today, the Agilent DTS is enabling a more thorough view of streamflow dynamics by providing a cost-effective way to make distributed measurements. Looking to the future, distributed sensor technologies will enable new *in situ* measurements that address concerns ranging from pollutant tracking for environmental protection to irrigation measurements for precision agriculture.

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9. The workshop announcement is available online at oregonstate.edu/conferences/fiberoptic2007

10. For more information about hydrologic monitoring projects in the Walla Walla Basin see www.wwbwc.org/Projects/Monitoring_Research/Surface_Ground_Water_Hydrology.htm