The Acoustic Method

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Introduction
The EasyQ is a compact sensor that measures river flow velocity and water level (stage). It is appropriate for monitoring river discharge at sites where velocity is needed to supplement stage measurements. In the longer term, its ability to provide sufficient data to automate quality control will improve routine dissemination of river flow data.

The EasyQ produces data specifically to support automated data quality control. It measures velocity and signal strength in three cells, thus enabling validation of the data by comparison of the different cells. An integrated pressure sensor plus two independent stage quality parameters provide means to validate and automatically correct stage measurements. A fourth beam enables the EasyQ to detect changes in the depth of the nearby channel.

This report summarizes two test comparisons of the EasyQ with nearby sensors. In the White River, comparison of EasyQ velocities with other nearby velocity sensors shows that the EasyQ's velocity measurement is accurate to around 1%. Comparison with a nearby AVM shows that the EasyQ velocity is proportional to the velocity averaged across the full width of the river. This result suggests that an EasyQ's velocity, measured at the side, can produce index velocities appropriate for estimating the discharge of the river. At Fall Creek, the EasyQ stage readings matched a nearby shaft encoder with a standard deviation of 4.7 mm. The EasyQ flagged several of its stage data points bad, and its pressure sensor provided the basis for accurate reconstruction of the missing data.

The EasyQ belongs to a family of sensors that also comprises the EasyV, the Aquadopp and the Aquadopp Profiler. The EasyV is a sensor that measures the horizontal velocity only, while the Aquadopp is a single point current meter. The Auadopp Profiler measures 3D current profiles in up to 128 levels of a water column, with down to 12 cm vertical resolution.

A short introduction to the Index Velocity Method is also given.

Background
Doppler current meters have a history dating back to the early 80s within the oceanographic community, where it has been used to measure remotely the speed and direction of water in applications ranging from scientific studies to permanent monitoring of harbors, coastal areas and offshore installations.

Doppler current meters operate by sending out sound pulses along very narrow beams in the water. As these pulses propagate through the water small portions the signal are reflected back by particles in the water. If these particles move relative to the instrument at the time they are hit by the acoustic energy from the transmit pulse the reflected signal will have a different frequency from the transmitted signal. This frequency shift is proportional to the relative velocity of the reflecting particles, and it is commonly referred to as the Doppler shift. Doppler current meters measure the Doppler shift of the reflected sound pulses, and by knowing the geometry of the instrument, combining this with the measured beam velocities they calculate 2D or 3D velocity vectors.

The obvious advantage of Doppler current meters is that they use acoustics to measure the velocity of water. They have, in other words, no moving parts with slow bearings that can get out of calibration or even stop due to extraneous matter blocking the movement. These sensors also never need calibration, and they don't drift as time goes by. The other unique feature of Doppler current meters is that they measure remotely. The measuring volume lies at a distance from the sensor itself. These sensors have, in other words, no physical structures in the measuring volume that may disturb the flow itself.

In spite of their many obvious advantages Doppler current meters for many years remained, however, instruments with relatively few users, and the main reason for this was probably cost. They were very expensive compared with sensors built on conventional technology, and they remained like that all up to the beginning of the 90s. That is when new companies came on the market, offering competitive Doppler-based current meters to particular segments in the oceanographic sector, which in turn caused the prices of these products to drop to half of what it used to be.

In the field of oceanography, Doppler-based flow sensors were first introduced in the scientific community, and they were later on taken into use in operational and permanent monitoring applications. As a result of this, the Doppler technology is now very well established as state of the art for water motion measurements among oceanographers around the world. For rivers and freshwater measurements it was, however, not until the introduction of quick and easy discharge measurements using a small boat and an Acoustic Doppler Current Profiler that a gained interest for Doppler sensors started to grow. The low price of today's Doppler sensors, combined with their ease of use and reliability facilitate permanent monitoring also in rivers using these sensors.

The EasyQ sensor for permanent river monitoring

The Nortek EasyQ sensor is an implementation of the well-established principles for Doppler-based measurements of water motion. What Nortek did when developing the EasyQ was to study what type of information would be really helpful when permanent monitoring of rivers was the issue. We soon found out that there was a need for more information than just the velocity of the water. Obviously, stage was a key parameter, and we also found that at many places information about bottom conditions and scour would be really helpful. The result of our studies led to the development of EasyQ.

The EasyQ (Figure 1) is a small, integrated sensor designed to monitor river flow velocity and stage. It is particularly well suited for sites that require velocity in addition to stage to obtain accurate discharge measurements. Such sites often have Acoustic Velocity Meters (AVMs). The EasyQ is an attractive alternative to an AVM because it is smaller, easier, and less expensive to install, and because it obtains more reliable data. In the longer term, the EasyQ should find applications in other sites as well. Its easy and unobtrusive installation is attractive compared to traditional stilling wells, and the addition of velocity data will improve discharge estimates compared to using stage measurements only. Even more interesting in

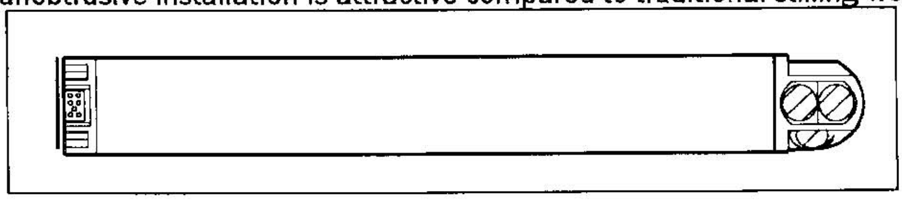

Figure 1. EasyQ River Monitor. Dimensions: 586 mm × 75 mm; weight: 1.7 kg. The transducer head on the right holds four beams: the two beams facing you measure velocity, one beam on top(not visible) measures water level and the bottom beam slants downward at 45 degrees to monitor the riverbed.

the long term is the fact that the EasyQ provides new means to automate data correction and data quality control. This process will reduce labor and speed dissemination of quality-controlled river flow data.

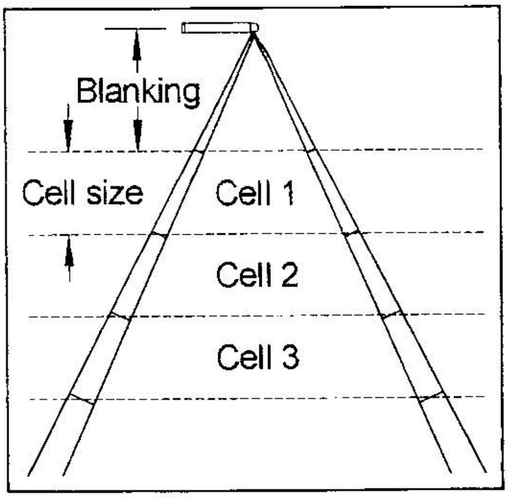

Figure 2. Plan view of the EasyQ velocity cells. Blanking is adjustable up to 10 m and cell size is adjustable between 0.4 and 2 m.

The EasyQ measures water velocity, echo intensity, water level, water pressure, tilt and temperature. It has four acoustic beams. Two horizontal beams measure velocity in three cells spaced horizontally across the river (Figure 2). A vertical beam looks up to measure the distance to the water surface and a fourth beam looks down at 45 degrees to monitor changes in the riverbed. Echo backscatter measured simultaneously with velocity provides qualitative information about sediment load in the river plus a means to detect interference in the velocity cells. The EasyQ's silicone piezoresistive pressure sensor participates in the stage algorithm by assisting detection of the surface echo (versus echoes from debris and other spurious echoes). It also provides independent data to validate the water level measurements. The EasyQ uses temperature to compute sound speed and provides tilt data to ensure that the stage beam is installed vertically. Data communication uses RS232 or SDI-12.

A simpler version of the EasyQ called EasyV also exists, measuring velocity but not stage, pressure or tilt.

This paper focuses more attention to the EasyQ's stage measurements than its velocity measurements. The EasyQ's velocity measurements have a long history and its ability to measure accurate velocity is already well established. Its acoustic stage measurement is new.

Test results
Several tests conducted in cooperation with the USGS have demonstrated the EasyQ's ability to provide reliable stage and velocity measurements. These tests have also been documenting the validity of the index velocity method.

Measurements were made at two sites in the Indianapolis metropolitan area. The White River is a medium-sized upland river with a mean annual flow of 58 m^3/s, and Fall Creek at Millersville is a smaller river with a mean annual flow of 8.3 m^3/s. Both sites are subject to large flow variations, but because the Fall Creek site is downstream from a dam, its flow tends generally to vary less. The channel at the White River site is 36 m wide and was about 2 m deep when the measurements started. The Fall Creek channel is 15 m wide and was 0.9 m deep when measurements started. At both sites, the EasyQ was installed about 0.3-1 m below the water during relatively low flows. In each case, the EasyQ was installed on the vertical wall of a concrete bridge support.

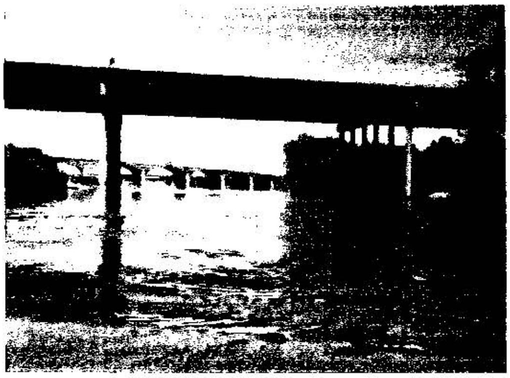

Figure 3. The White River test site is on the east (right) bridge support.

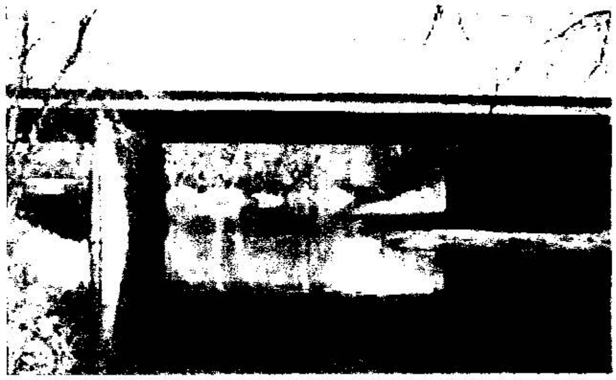

Figure 4. The Fall Creek at Millersville. The EasyQ is installed on the concrete bridge support.

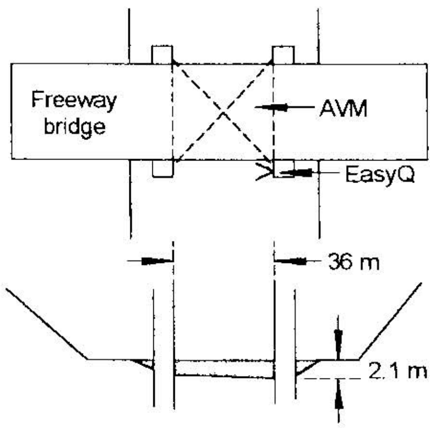

Figure 5. Plan view of White River installation site.

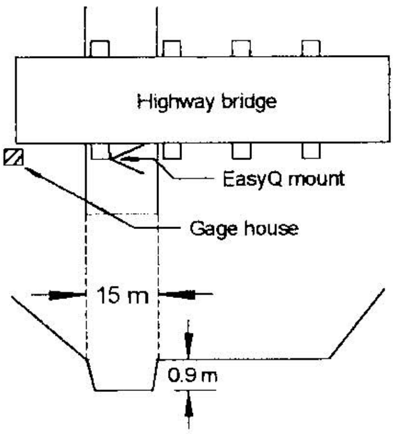

Figure 6. Sketch of the Fall Creek deployment site

The White River site included a permanently-mounted Acoustic Velocity Meter (AVM) plus a Doppler Current Meter (DCM) temporarily mounted next to the EasyQ. The AVM also measures stage acoustically. The Fall Creek EasyQ was installed near a shaft encoder, and data from both the shaft encoder and the EasyQ were logged with the same SDI-12 data logger.

Tilt is a factor in the quality of the EasyQ stage measurement, and the EasyQ should be installed with tilt of about 3° or less for reliable surface detection. The prototype EasyQ used in the White River test had no tilt sensor and was installed with an unknown tilt (estimated to be around 5°). The production version EasyQ includes an internal tilt sensor plus installation software that enables quick verification of both installed tilt and stage data quality. The EasyQ's tilt at Fall Creek was 3° for the data shown here.

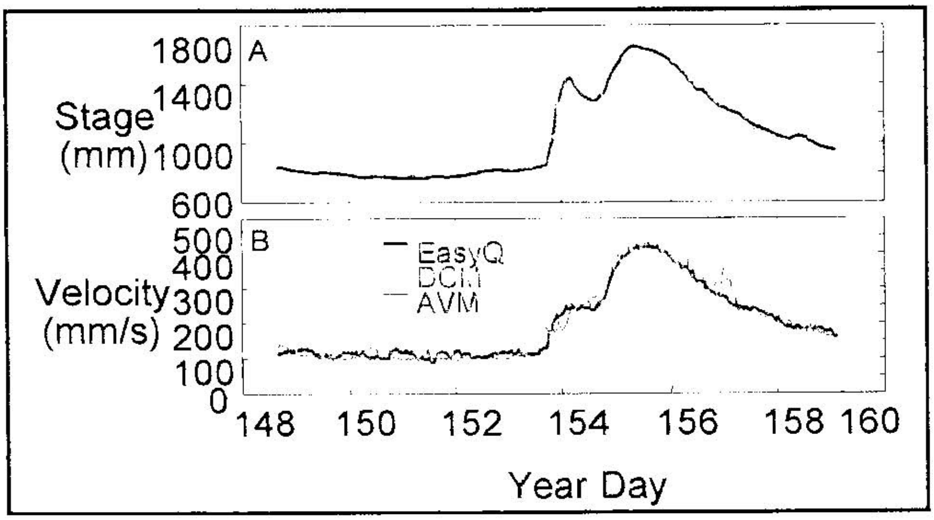

Figure 7A. Stage measured by EasyQ (heavy line) and AVM (thin line). The AVM line is barely visible behind the EasyQ line. Day 148 corresponds to May 27, 1999.

Figure 7B. Velocity measured by the EasyQ, a current meter (DCM), and an Acoustic Velocity Meter (AVM). Spikes in the AVM data are visible behind the EasyQ data, but the DCM and EasyQ lines are nearly coincident, making the DCM visible in only a few places

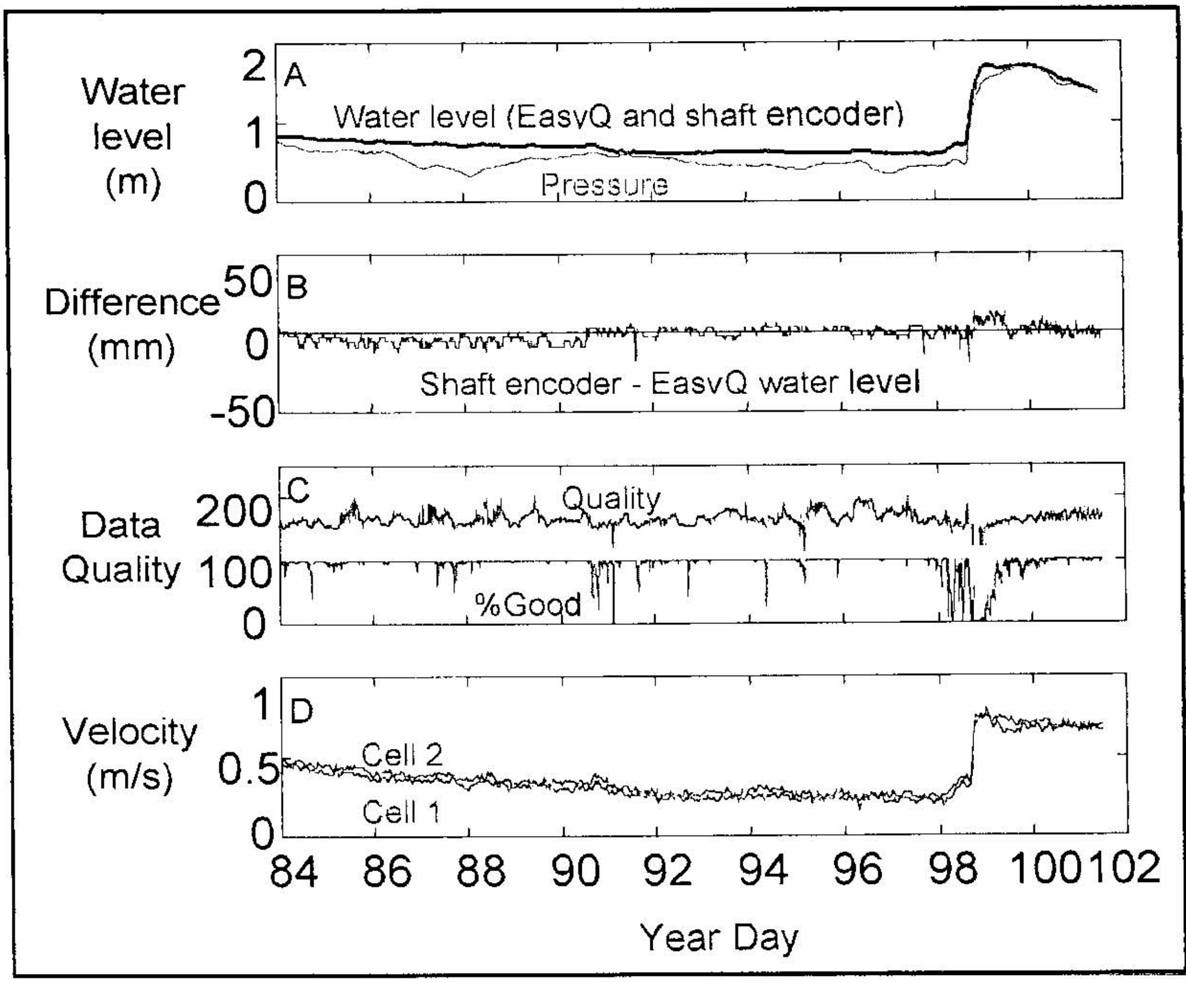

Figure 8. Water level measured by EasyQ and shaft encoder (A), difference between shaft encoder and EasyQ (B), the EasyQ stage quality and % good parameters (C), and the measured velocities in cell 1 and 2 (D). Day 84 corresponds to March 24, 2000.

Stage Observations

The EasyQ's stage algorithm identifies peaks by the size of a computed quality parameter—the better an echo matches the expected shape of a surface echo, the higher the quality value. While the prototype EasyQ used in the White River test selected the first echo for which the quality value rose above a certain threshold, and then measured the distance to the center of the echo, the Production EasyQ improves on the prototype algorithm in several ways. The quality computation is better and more sensitive, but the largest improvement is addition of a pressure sensor to assist identification of the surface echo. The pressure sensor sets a window around the surface, and the EasyQ then select this first peak within the window that exceeds the threshold.

The production EasyQ stage algorithm consists of a series of 1-s realization during its measurement interval, averaging the result into a single reported value. Each realization consists of a large number of pings, and the EasyQ must find at least one peak within the near-surface pressure window, or else the realization is flagged bad. The EasyQ's "% good" parameter tells you how many realizations were good—one good realization is adequate to produce a reliable result. The Fall Creek data were obtained with a 60-s stage measurement interval consisting of 60 realizations. In addition to the % good, the EasyQ also outputs the average value of the stage quality during each measurement interval.

The prototype EasyQ stage measurements (Figure 7A) were noisy—about 4% of the data were spikes (corrected using a spike-removal algorithm). The production EasyQ's stage algorithm has been improved over the prototype EasyQ, and as a result, the Fall Creek data (Figure 8A) were much better. There were no spikes in the data. About 1% of the data were flagged bad and corrected by interpolation in post-processing. Both the AVM and the shaft encoder data required cleanup as well, the AVM data to remove spikes and the shaft encoder to remove a sudden offset.

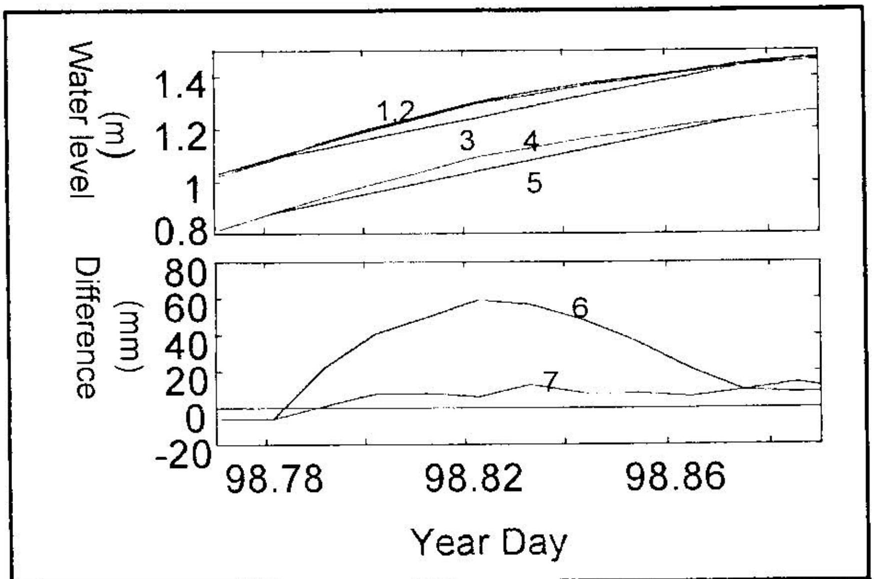

Figure 9. Interpolation of stage data. (1,2) EasyQ corrected stage and shaft encoder stage. (3)EasyQ stage corrected with only linear interpolation. (4) EasyQ pressure. (5) Linearly interpolated pressure, using the same endpoints as used for trace 3. (6) Difference between shaft encoder stage and trace3. (7) Difference between final corrected stage and shaft encoder stage.

Table 1 summarizes the standard deviation of the difference between the EasyQ and its comparison stage reading. The standard deviation measures how well the different readings track each other—mean offsets are not meaningful because stage sensors are always require an offset to produce readings relative to the local datum. Figure 8B plots the difference between the Fall Creek EasyQ and the shaft encoder.

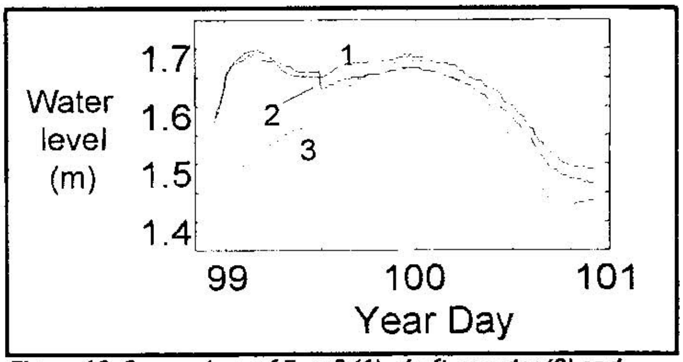

Figure 10. Comparison of EasyQ (1), shaft encoder (2) and pressure (3) time series.

Automated Stage Data Correction

The EasyQ provides new, unique capabilities that improve automated data quality control and correction. This section shows how the pressure sensor substantially improved interpolation of a short segment of missing data. It also shows an example of how the EasyQ data enabled detection of a sudden shift in the shaft encoder output. Small shifts, such as the one observed here, can be difficult to see in typical hydrographs, particularly if the water level varies as much as it did at Fall Creek.

The production EasyQ flags bad data with its "% good" parameter. Figure 8C plots the "% good" plus the quality of the stage peak echo. In Fall Creek zero "% good" flagged 16 bad stage values out of the 1667 readings.

Table 1. Standard deviation of the difference between the EasyQ stage readings and the comparison stage sensor.

	Difference
White River (AVM)	6.0 mm
Fall Creek (shaft encoder)	4.7 mm

We corrected the missing EasyQ stage data with an interpolation process, assisted by the pressure data. Figure 9 shows a data segment with 8 consecutive missing data points. Trace 3 shows the EasyQ stage, linearly interpolated between the nearest good data points—trace 3 deviates from the shaft encoder stage (trace 2) by as much as 60 mm (trace 6) because the water level was not changing linearly during this interval. The EasyQ pressure (trace 4), however, varies like the actual stage (trace 2) over this short time scale, even though atmospheric pressure changes cause pressure to drift over longer time scales. We computed a correction value as the difference between the pressure (trace 4) and the straight line (trace 5), then added this correction to trace 3. The result (trace 1) closely matches the shaft encoder stage (trace 2). The final difference (trace 7) is thus reduced to less than 10 mm.

The shaft encoder data exhibited a sudden shift in output during these measurements. Figure 10 shows a detail of the shaft encoder stage, EasyQ stage and pressure. The shaft encoder shows a sudden offset of 21 mm at time 99.5, but none of the other data show a similar shift. This indicates that the shift can only be a change in the shaft encoder itself. The shaft encoder data were corrected by offsetting subsequent values by 21 mm.

Velocity Data

All velocity data were averaged into hourly intervals. None of the EasyQ or DCM velocity data were edited. The standard deviation of the difference between the EasyQ and DCM velocities was 5 mm/s.

The AVM data were edited to correct spikes and dropouts (it appears likely that errors remain in the AVM data). The AVM data, as installed, are unscaled (the index velocity method does not require the use of scaled velocity readings). For purposes of this comparison, the AVM data were scaled so that the mean AVM reading matched the mean EasyQ reading. Figure 7B shows the EasyQ, DCM and AVM data. The standard deviation of the difference between the AVM and either the EasyQ or the DCM is 20 mm/s. The residual errors in the AVM are the likely reason for the larger difference. The fact that the EasyQ and AVM data matched well overall supports the idea that velocity measured at one location in a river is suited for estimating the discharge of the whole river.

Figure 8D shows velocity from the first two cells of the Fall Creek EasyQ. The third cell appears to see periodic interference during low flow and could not be used for velocity measurements. The velocities in the first two cells track each other closely, differing from each other in the mean by about 5%. Both flows are aligned on average within 5 degrees of the axis of the channel.

Automated Data Quality Control

The EasyQ is designed to provide a wide range of data to facilitate automated data quality control. One goal of automated data collection is to disseminate data as soon as possible. Data is often disseminated today with minimal or no quality control, or it is delayed until someone reviews the data first. The EasyQ improves this situation by providing sufficient data to enable automated processes to detect and correct data problems. These processes could improve data quality by detecting and correcting problems that would slip through human review. Good automated processes could substantially reduce labor hours required for human review by flagging trouble spots that need attention, and it could speed up the dissemination of quality-controlled river flow data.

In addition to the intrinsic quality-control parameters (i.e. the "% good" parameter), the EasyQ's redundant information provides added means for quality control. For example, river stage and water pressure both vary relatively slowly. Sudden errors in one sensor are unlikely to occur at the same time in the other. Simple filtering and comparison algorithms can detect these sudden differences. Velocity data can be screened individually by comparison with one another, and by the use of the signal strength. Sudden passage of a ship, for example, could appear as a spike in the echo intensity data. Normal channels will produce flow velocity and signal strength that is roughly the same in all three velocity cells. If something begins to interfere with one cell (e.g. weeds), both velocity and signal strength in that cell will begin to deviate from the other cells. Automated processes can detect these deviations when they rise above a certain threshold.

EasyQ applications

The EasyQ has several applications in river monitoring. Among these are

1) Flash floods

   In many areas of the world a combination of relatively shallow and at the same time steep rivers leads to very intensive flooding conditions during heavy rain or typhoon conditions. These extreme situations have always been a problem when it comes to establishing Qh calibration curves, because it is too dangerous to manually measure the velocity of the water during these events. With the EasyQ it is possible to measure both water level and the velocity even when such extreme situations appear. The robust and streamlined design of the EasyQ also reduces the risk of sensor damage due to physical impacts from floating debris. The sensor can even be built into a protecting shield, having only small openings for the acoustic paths in front of the transducers.

2) In some areas the calibration curves tend to change with changing river conditions. This is for example true for rivers where a thin layer of ice at periods covers the bottom. This will alter the bottom roughness, and may lead to a different discharge, even though the water level stays the same. Also, in rivers with heavy vegetation one may experience a different discharge for a certain water level, depending on the amount of vegetation in the river. Again, the Qh relation is non-stationary. In rivers were these phenomena appear the EasyQ can be a very powerful tool, because it measures not only stage, but also the velocity of the water, and it is obvious that if for a certain water level the discharge varies the velocity will also vary.

   In this context it is also worth mentioning that the EasyQ can be permanently deployed under the ice of ice-covered rivers. It will then measure the distance to the underside of the ice and this information, together with velocity measurements will provide data that makes it possible to calculate discharge with high precision, also during periods with ice covering the river.

3) Flash floods represent a major measurement challenge, because these rivers are either completely dry or have extremely little water for most of the time. Then, during rainy periods the rivers will be full of water for a short period of time. Normally, these conditions arise with almost no lead-time. It is, in other words, no time to install equipment when the situation arises. The sensors must be capable of being in air most of the time, and still be able to measure when they are covered by water. The EasyQ can do that, and it won't be damaged or get out of calibration, even with long periods in the air.

4) Measurements during extreme situations can be problematic, either because it is too dangerous or because the water level is very low and/or the event lasts for only a very limited period of time. Even though the EasyQ does not provide complete profiles or a measurements matrix like a manual impeller measurement would give it is able to perform during all kinds of flow situations and, hence, can provide very valuable information about the stage and velocity conditions during these extreme situations. Further, it does so automatically.

5) Sites where stage alone is too limited to provide good estimates of discharge. Rivers regulated by hydropower plants, for example, may have varying discharge while the stage stays more or less constant. For applications like this the EasyQ stage and velocity data will provide additional information that will improve the discharge calculations over those based on stage alone.

The Index Velocity Method

The EasyQ provides the data needed for the index velocity method developed by US Geological Survey for estimating river discharge. The traditional stage-discharge method is based on an empirical relationship between measured discharge and stage. The index velocity method uses stage as a means to obtain the river cross-sectional area. The relationship between stage and area can be based on the standard river cross-section for the site. The EasyQ's velocity provides an index used to estimate the mean velocity in the river. The ratio of the index velocity to the mean velocity may depend on the stage, and this relationship can be based on river discharge surveys.

Mathematically the method can be expressed as follows:

$$Q = Area*U_{AVM}*C = Area*(U_{EZQ}*B)*C = Area*U_{EZQ}*C'$$

where the Area depends on the water level (stage) and the bottom profile, U_{AVM} is the velocity measured by a time of flight system, U_{EZQ} is the velocity measured by the EasyQ in a subset of the river, and where C and C' are constants that need to be calibrated for a particular installation. The essence of the Index Velocity Method is that $U_{AVM} = U_{EZQ}*B$, which means that the velocity measured by the EasyQ in a subset of the river is proportional to the mean velocity across the river.