Better flow measurements in slow, weedy streams - using the Rising Bubble method

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Background

The problem

In Hawke’s Bay, irrigation bans are triggered when water flows drop below the consented limits (e.g. minimum flow limit). When bans come into force, the heat is on everyone – fish, irrigators and hydrologists. We need to get the numbers right, especially during these critical times.

But conventional gauging methods are ineffective in slow, lowland, weedy streams.

It is understandable that gaugings at 0.6 of depth might *over*-estimate flow, when weed beds create a thicker layer of still water near the bed. Then we discovered that two-point gaugings (at 0.2 and 0.8 of depth) *under*-estimated flow in this situation.

This indicates an urgent need for more-accurate methods to gauge lowland weedy streams.

Doyle *et al.* (2015) also demonstrated that measurements at 0.6 of depth can *over*-estimate column velocity, and recommended at least three-depth measurements (0.2, 0.6 and 0.8) in this situation.

But we cannot tell, by looking at the stream, if flows are lamina. For example, invisible still-water zones extend an unknown distance downstream from visible weed beds. One rule-of-thumb is to change the method, from 0.6 of depth to 0.2 and 0.8, at depths greater than 0.5 m. This rule is at best unreliable, and at worst counterproductive, especially since weed and boulders will have more effect on the flow depth in shallow streams.

The challenge

The search for better methods led Hawke’s Bay Regional Council to develop a new type of flow-meter that uses the rising-bubble method (Figure 1).

After constructing a prototype ‘rising-bubble’ meter, we set out to answer the first question - does it work? We conducted field tests alongside other flow meters, but this raised another question - which meter gave the right answer?

We needed an accurately-known reference.

NIWA’s velocity-rating tank provided that reference. This was critical for testing the method because it provides a series of programmable speeds in a controlled environment.

Figure 1 Rising-bubble method in action - the wading rod prototype for flow measurements.

The Rising-Bubble Method Explained

The rising-bubble method is different to that of a conventional flow gauging.

- Conventional gauging uses water velocity and channel cross-sectional area
- Rising-bubble gauging uses bubble rising-velocity and surface bubble-displacement area

For the rising-bubble method, a bubble released from the bed of a flowing stream will reach the water surface at some distance downstream. The *faster* the water, the *further downstream* the bubble is displaced. And the *deeper* the flowing water, the *further downstream* the bubble is displaced. If the velocity near the bed is zero, then the bubble will rise straight up until it encounters moving water.

If we measure bubble displacement at, say, 20 offsets across the width of a stream we can calculate the surface bubble-displacement area. Flow is then calculated by multiplying the surface bubble-displacement area (rather than the channel cross-sectional area) by the bubble rising-velocity (rather than by the water velocity).

The rising-bubble method is not a velocity-area method, but the field method and calculation are similar. For example, Hilltop Manager software can be 'tricked' into calculating the correct flow by entering bubble displacement as water depth, and entering bubble rising rate as water velocity.

The rising rate of bubbles has been the subject of much research for various engineering and environmental applications (Kulkarni & Joshi, 2005), but little research has been done for river flow measurement. With a handful of publications since the 1970's (John *et al.*, 1978; Meenakshisundaram, 1980; Sargent, 1981; Toop *et al.*, 1997), development of the method was spasmodic until the Delft University of Technology (The Netherlands) commenced research into photogrammetry methods for fixed installations (Hilgersom & Luxemburg, 2012; Hilgersom *et al.*, 2014).

Fixed installations have a lot of potential, but this article focuses on the wading method both as a priority and a precursor to fixed installations.

Methods

Field trial

We carried out flow measurements in a weedy stream (Raupare at Ormond Rd), using three methods:

- boat-mounted ADCP,
- wading rod-mounted ADV
- rising bubble

The test site is normally gauged using a wading rod-mounted ADV (Sontek Flowtracker). We measured velocity at 0.2, 0.6 and 0.8 of depth and then extracted conventional gaugings in post-processing (0.6 of depth, 0.2 and 0.8 of depth). We performed eight passes of ADCP measurements over a total elapsed time of 22 minutes (Sontek River Surveyor M9). This site also has an upward-looking ADCP logger installed (Sontek IQ standard) and this confirmed little flow change between measurements.

Lab experiment (13 May 2015)

NIWA rates (calibrates) water current meters at its rating tank (Figure 2) located at Kainga just north of Christchurch. The rating tank provided a unique opportunity to test the rising-bubble wading rod developed by Thomas Wilding at Hawke's Bay Regional Council.

An electric motor propels the rating car along the water-filled rating tank, resembling a long, narrow swimming pool (50m long, 2m wide, 1.7m deep). The car tows the current meter through stationary water at a programmed, accurately-known velocity.

Figure 2 Right tool for the job – the velocity rating tank operated by NIWA Instrument Services at Kainga (Canterbury).

The rating car provided a velocity reference that enabled us to compare the rising bubble method against other variables, including:

supply air pressure	(0.05, 0.1, 0.15, 0.2 and 0.25 MPa)
water velocity	(0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1.0 m/s)

Supply air pressure

This is an important variable with the potential to change bubble size and shape, and consequently the bubble rising-rate. The prototype meter uses an unregulated air supply, so pressure declines over the period of a field measurement.

We measured the bubble displacement for each air-pressure increment, while keeping other variables constant (i.e. setting on air flow valve, nozzle depth 0.5 m, car velocity 0.3 m/s, side exit nozzle 46 mm long with 1 mm orifice). The air flow valve was set to achieve a bubble rate of about three to ten bubbles per second.

The air pressure was held constant at 0.25 MPa for the first run. We then changed the supply-pressure from the compressor tank for each run (0.2, 0.15, 0.1 and 0.05 MPa), which would translate to a changed, but unmeasured, pressure at the nozzle after passing through the air control valve. Bubble displacement was measured for each run, and converted to bubble rising-rate for analysis (rising rate = [car velocity x depth] / displacement).

Water velocity

This is important for flow measurements, so we investigated how robust the method is over a range of velocities. It's important to note that the rising-bubble method *does not measure velocity directly*. Instead, it combines velocity and depth to measure unit-discharge (m^2/s) at each sampling position across a stream. To derive velocity we simply divide unit-discharge by depth.

We measured bubble displacement for each velocity increment, while keeping air-pressure and other variables constant (air pressure 0.15 MPa, fixed setting on air flow valve, nozzle depth 0.23 m, side-exit nozzle 46 mm long with 1 mm orifice).

The water temperature remained reasonably stable during the experiment (12.2 to 13.0 C). We verified this by measuring before, during and after the trials, at two depths (0.3 and 0.7 m). Atmospheric pressure also remained stable (99.2 to 99.5 MPa at sea level).

We measured the surface displacement of rising bubbles for each rating car run, visually, using a ruler fixed a few centimetres above the surfacing bubbles. Most measurements were made over a distance of 5 m, though longer distances were needed at higher velocities (15 m at 1 m/s). In future tank experiments we may be better to standardise elapsed time, rather than distance, depending on the uncertainties in the measurement of the rating car's reference at lower speeds.

Results and Discussion

Field investigations

We carried these out in a rectangular concrete flume with weed beds upstream. This provided several important insights:

In comparison to a three-depth measurement (0.2, 0.6 and 0.8 of depth), carried out on 13-Feb-2015:

- a one-depth measurement (0.6 of depth) would have overestimated flow rate by 7%
- a two-depth measurement (0.2 and 0.8 of depth) would have underestimated flow rate by 7%,

So, a change of gauging method, from one-depth to two-depths, might have erroneously indicated a 14% drop in flow.

We then cleared the upstream weed beds and compared the rising bubble method and an ADV gauging (at 0.6 of depth) with an ADCP gauging (26-Feb-2015). We got the following results:

- Depth-integrated ADCP - 351 L/s
- ADV measured at 0.6 of depth – 368 L/s; giving the highest flow estimate (5% higher than the ADCP)
- The rising-bubble method - 355 L/s, (1% higher than the ADCP)

The rising-bubble method appears better than a single-depth gauging, although this is not conclusive because all measurements were estimates. For example, the blanking areas of an ADCP require extrapolation of near-bed velocities where weed-effects will be most pronounced. Hence we carried out the lab experiments at NIWA's rating tank to compare measurements against a series of accurately-known reference velocities.

Lab experiments

Handling the pressure

The rating tank experiments revealed the rising-bubble method was relatively insensitive to changes in supply air pressure (Figure 3) - a good thing.

There was a slight decline in rising-rate as pressure increased, probably because of increased bubble size. But that decline in rising-rate was small. For example, starting a flow measurement at a pressure of 0.2 MPa and finishing with 0.1 MPa is expected to result in a 1% decline in bubble rising-rate. A 1% error in rising-rate translates directly to a 1% error in measured flow. Though it is a small change, we could correct for it by applying the average of the bubble rising-rates, measured just before and just after the flow measurement.

To ensure the bubble supply does not stop part way through a flow measurement, it would be best to set the air control valve to produce bubbles in the deepest part of the cross-section (greatest pressure needed) before starting the measurements.

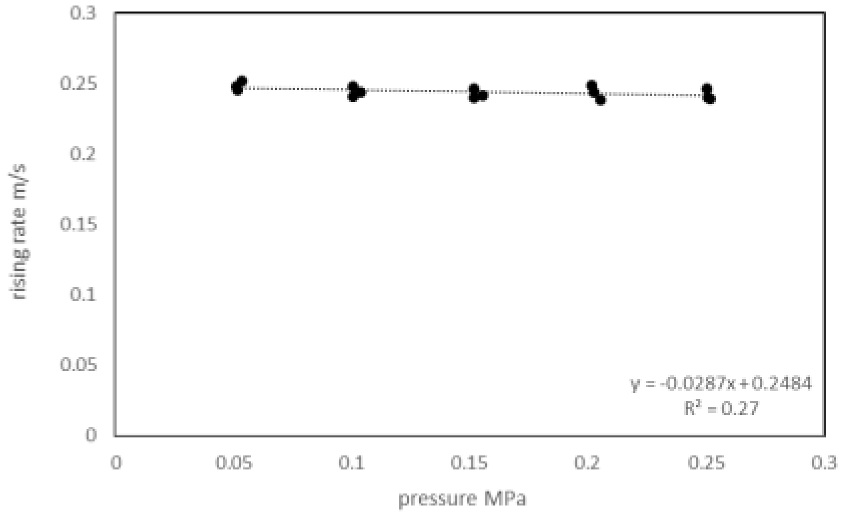

Figure 3 Change in bubble rising-rate with supply air pressure.

Velocity limitations revealed

The rating tank experiments demonstrated that the rising-bubble method responded linearly to velocity for a given depth (Figure 4) - a good thing.

But velocities exceeding 0.7 m/s were difficult to measure, as reflected in the scatter of the data points. We had to repeat runs at higher velocities because it was difficult to locate the surfacing bubbles. Increasing turbulence at higher velocities (from the wading rod) also made the rising bubbles difficult to see, and this was compounded by the greater spread of bubbles across the surface. At a velocity of 1 m/s, the bubbles were surfacing at an angle of 13°, compared to 36° at 0.3 m/s. Natural turbulence (e.g. riffles) in a flowing stream would only add to this problem.

For wading methods, there is a limit to how far downstream you can measure bubble displacement while holding the rod. This problem made guess-work of flow measurements in the Tutaekuri-Waimate Stream, where bubbles were displaced up to 2 m downstream (max depth 0.96 m, velocity 0.6 m/s). So far we've found that surfacing bubbles are 'out of reach' at depths and velocities that make wading difficult. You can get a rough idea of displacement distance for your stream using the equation: *displacement* = [*velocity* x *depth* x 4].

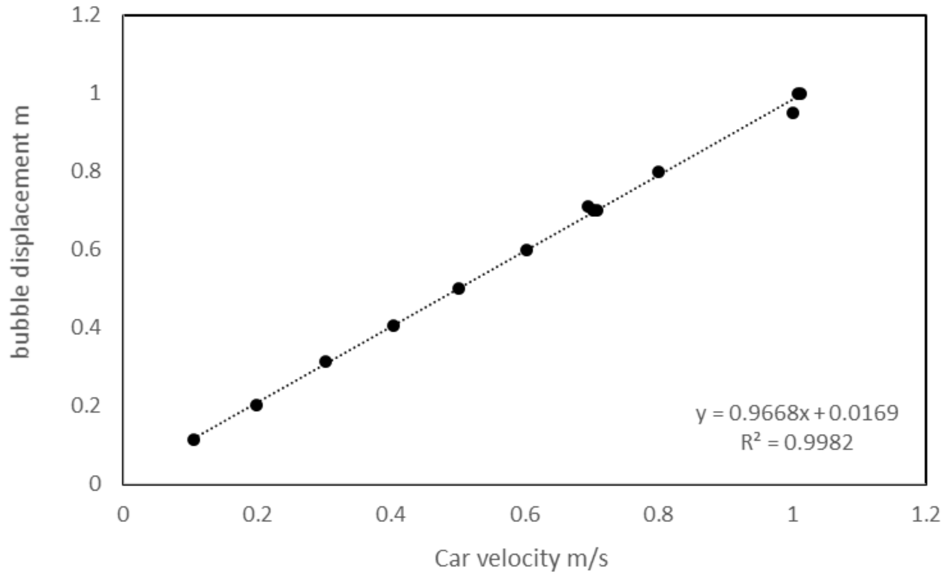

Figure 4   Change in measured bubble displacement with increasing velocity of the rating car, for a fixed depth (0.23 m).

Measuring bubble rising-rate in the field

We estimated bubble rising-rate in the field using a handheld stopwatch to measure the time taken for a bubble to reach the surface. Here we completed 10 replicates before the flow measurement and 10 after. This accounted for changes in air-supply pressure. We then calculated the median time from all 20 replicates and converted it to a rising rate by dividing the nozzle depth by time.

We compared results from the stopwatch method to the rising-rates derived from the rating tank measurements (rising rate = [car velocity x depth] / bubble displacement). Our stopwatch estimates exceeded the tank-derived values by 4% and 9% (from two sets of 20 measurements at different depths and air pressures). The biggest source of error, of those we investigated, is therefore the field measurement of bubble rising rate.

The rising-rate of bubbles has been studied in detail for a wide range of industrial applications (e.g. power stations, wastewater treatment, breweries), (Abdulmouti, 2014). Factors known to affect the rising rate of bubbles include:

- Bubble size
- Surface tension
- Water density and viscosity

Rising-rate does not increase linearly with bubble diameter (Baz-Rodríguez *et al.*, 2012). Instead it displays a minimum velocity (about 0.25 m/s) for bubbles of about 6 mm diameter. Aiming to produce '6 mm bubbles' minimizes sensitivity of rising-rate to small changes in bubble size (e.g. expansion as the bubble rises to the surface), compared to more rapid change in velocity for bubbles less than 2 mm or greater than 10 mm diameter. Hilgersom and Luxemburg (2012) recommended nozzle orifices of 1mm diameter, as these produced bubbles within this stable-velocity size range.

However, the effects of other factors remain, including contaminants that change surface tension and temperature changes that affect water density and viscosity. These changes are significant because a 10% error in rising-rate would translate directly to a 10% error in the flow measurement. That is why it is important to measure the rising-rate in the field for each flow measurement.

Conclusions

A boat-mounted ADCP is better suited to streams that are too deep and fast for the rising-bubble method.

For shallow and fast (greater than 0.7 m/s) streams, conventional ADV's and propeller meters are less-affected by surface turbulence than the rising bubble method.

So rather than replacing existing equipment, the rising bubble method would be complementary, because it would extend the types of streams for which accurate flow measurements are possible. The method is best suited to slower-flowing streams, and it is robust to non-lamina flows created by weed beds.

Where to from here?

The field measurement of bubble rising-rate was the biggest source of error, of the factors we investigated. We therefore need a method to determine the bubble rising-rate more accurately than we can achieve with a stop watch.

This is a promising area of research because there is potential to measure the rising-rate accurately in a controlled environment for either a sample of stream water, or better, in-situ, measuring rising-rate in real time, before and after each flow measurement.

Eventually, we aim to develop a system for permanent installation; one that can measure total stream discharge continuously and automatically, digitally analysing the position of bubbles as they surface.

If you would like updates on further development, or want to participate in future development, please contact...

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