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Citizen science flow - an assessment of citizen science streamflow measurement methods

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Abstract. Wise management of water resources requires data. Nevertheless, the amount of streamflow data being collected globally continues to decline. Involving citizen scientists to generate hydrologic data can potentially help fill this growing hydrological data gap. Our aim herein was to (1) evaluate three potential citizen science streamflow measurement methods (i.e. float, salt dilution, and Bernoulli run-up), (2) select a preferred approach, and (3) pilot test the selected approach at a larger scale. We performed 20 side-by-side evaluation measurements in headwater catchments of the Kathmandu Valley. We used mid-section measurements from an acoustic Doppler velocimeter as reference flows. Evaluated flows ranged from 0.006 to 0.240 $m^3 s^{-1}$. Linear regressions forced through the origin for scatter plots with reference flows had slopes of 1.05, 1.01, and 1.26 with r-squared values of 0.90, 0.98, and 0.61, for float, salt dilution, and Bernoulli run-up methods, respectively. After selecting the salt dilution method as the preferred approach, we performed larger scale pilot testing in a one-week Citizen Science Flow campaign (CS Flow) involving 20 volunteers. Observed flows (n = 145) ranged from 0.0004 to 0.425 $m^3 s^{-1}$ and were distributed among the 10 headwater catchments of the Kathmandu Valley. At locations with reference flows available (n = 5), a linear regression forced through the origin between reference flows and CS Flow measurements had a slope of 0.90 with an r-squared value of 0.97. Future work should evaluate the feasibility of applying citizen science salt dilution streamflow measurements to larger regions.

1 Introduction

Lord Kelvin, a 19th century Scottish physicist and mathematician, wisely said, "… the first essential step in the direction of learning any subject is to find principles of numerical reckoning and practicable methods for measuring some quality connected with it (Kelvin 1883)." With regards to our natural resources, if we aim to wisely steward them, we must first learn to measure them. While it might sound trivial, collecting and, worse yet, interpreting point measurements of precipitation, evapotranspiration, infiltration, and soil moisture at the catchment scale is fraught with challenges. Indeed, the importance of measuring streamflow is underpinned by the reality that it is the only truly integrated representation of the entire catchment that we can plainly observe (McCulloch 1996).

Despite growing demand, the amount of streamflow data actually being collected continues to decline in several parts of the world, especially in Africa, Latin America, Asia, and even North America (Hannah et al. 2011; Van de Giesen et al. 2014; Feki et al. 2016; Tauro et al. 2018). Specifically, there is an acute shortage of streamflow data in headwater catchments (Kirchner 2006) and developing regions (Mulligan 2013). The reasons for this trend are various, but the situation is perpetuated by a lack of understanding among policy makers and citizens alike regarding the importance of streamflow data, which leads to persistent funding challenges (Kundzewicz 1997; Pearson 1998). This is further compounded by the reality that the hydrological sciences research community has focused much of its efforts in recent decades on advancing modeling techniques, while innovation in methods for generating the data these models depend on has been relegated to a lower priority (Mishra and Coulibaly 2009).

Considering these challenges, alternative methods for generating streamflow and other hydrological data are being explored (Tauro et al. 2018). For example, developments in using remote sensing to estimate streamflow are being made (Tourian et al. 2013; Durand et al. 2014), but applications in small headwater streams are expected to remain problematic (Tauro et al. 2018). Utilizing cameras for measuring streamflow is also a growing field of research (Muste et al. 2008; Le Coz et al. 2010; Dramais et al. 2011; Le Boursicaud et al. 2016), but it is doubtful that these methods will be broadly applied in headwater catchments in developing regions in the near future because of high costs and lack of technical capacity. In these cases, however, involving citizen scientists to generate hydrologic data can potentially help fill the growing global hydrological data gap (Lowry and Fienen 2012; Buytaert et al. 2014; Sanz et al. 2014; Davids et al. 2017; van Meerveld et al. 2017; Assumpção et al. 2018).

Kruger and Shannon (2000) define citizen science as the process of involving citizens in the scientific process as researchers. Citizen science often uses mobile technology (e.g. smartphones) to obtain georeferenced digital data at many sites, in a manner that has the potential to be easily scaled (O'Grady et al. 2016). Turner and Richter (2011) partnered with citizen scientists to map the presence or absence of flow in ephemeral streams. Fienen and Lowry (2012) showed that citizen science text message based measurements of water level can have acceptable errors. Mazzoleni et al. (2015) showed that flood predictions can be improved by assimilating citizen science water level observations into hydrological models. Le Coz et al. (2016) used citizen scientist photographs to improve the understanding and modeling of flood hazards. Davids et al. (2017) showed that lower frequency observations like those produced by citizen scientists can provide meaningful hydrologic information. Van Meerveld et al. (2017) showed that citizen science observations of stream level class can be informative for deriving model based streamflow time series of ungauged basins.

While the previously referenced studies focus mainly on involving citizen scientists for observing stream levels, we were primarily concerned with the possibility of enabling citizen scientists to take direct measurements of streamflow. Using keyword searches using combinations of "citizen science", "citizen hydrology", "community monitoring", "streamflow monitoring", "streamflow measurements", and "discharge measurements," we could not find any specific work about how citizen scientists, equipped with modern tools like smartphones, could take streamflow measurements directly themselves. Instead, to develop potential citizen science streamflow measurement methods to evaluate further, we turned to the vast body of general knowledge about the collection of streamflow data.

Streamflow measurement techniques suggested in the United States Bureau of Reclamation Water Measurement Manual (USBR 2001) that seemed potentially applicable for citizen scientists included: deflection velocity meters consisting of shaped vanes projecting into the flow along with a method to measure deflection; the slope area method whereby the slope of the water surface in a uniform reach is measured and combined with the Manning formula; and pitot tubes for measuring velocity heads. The float and salt dilution methods described by several authors also seemed applicable (British Standards Institute 1964; Rantz 1982; Fleming and Henkel 2001; Escurra 2004; Moore 2004a, 2004b, and 2005; Herschy 2014). Finally, Wilm and Storey (1944) and Church and Kellerhals (1970) introduced the velocity head rod, or what we later refer to as the Bernoulli run-up method, involving measurement of stream velocity heads with a thin flat plate.

Based on these recommendations, the strengths and limitations discussed in the corresponding literature, and practical considerations about how citizen scientists could implement the different approaches, we selected three approaches for further evaluation: float, salt dilution, and Bernoulli run-up. Our primary aims in this paper were to (1) evaluate these three potential citizen science streamflow measurement methods, (2) select a preferred approach, and (3) pilot test the preferred approach at a larger scale.

2 Materials and methods

2.1 Citizen science streamflow measurement methods evaluated

The procedures for each of the three citizen science streamflow measurement methods evaluated are described in the following sections.

2.1.1 Float

The float method is based on the velocity-area principle. Total streamflow (Q) in cubic meters per second ($m^3\ s^{-1}$) was calculated with Eq. (1):

Eq. (1) $Q = \sum_{i=1}^{n} C * VF_i * d_i * w_i$

where C is a unitless coefficient to account for the fact that surface velocity is typically higher than average velocity (typically in the range of 0.66 to 0.80 depending on depth; USBR 2001), VF_i is surface velocity from float in meters per second (m s^{-1}), d_i is depth (m), and w_i is width (m) of each sub-section (i = 1 to n, where n is the number of stations). Surface velocity for each sub-section was determined by measuring the amount of time it takes for a floating object to move a certain distance. For floats we used sticks found on site. Sticks are widely available (i.e. easiest for citizen scientists), generally float (except for the densest varieties of wood), and depending on their density are between 40 and 80% submerged, which minimizes wind effects.

Float measurements involved the following steps:

1. Selected stream reach with straight and uniform flow
2. Divided cross section into several sub-sections (n, typically between 5 and 20)
3. For each section, measured and recorded
    a. The depth in the middle of the sub-section
    b. The width of the sub-section
    c. The time it takes a floating object to move a known distance downstream (typically 1 or 2 m) in the middle of the sub-section
4. Solved for streamflow (Q) with Eq. (1)

2.1.2 Salt dilution

There are two basic types of salt dilution flow measurements: slug (previously known as instantaneous) and continuous rate (Moore 2004a). Salt dilution measurements are based on the principle of the conservation of mass. In the case of the slug method, a single known volume of high concentration salt solution is introduced to a stream and the electrical conductivity (EC) is measured over time at a location sufficiently downstream to allow good mixing (Moore 2005). In contrast, continuous rate salt dilution method involves introducing a known flow rate of salt solution into a stream (Moore 2004b). Slug method salt dilution measurements are broadly applicable in streams with flows up to 10 m^3 s^{-1} with steep gradients and low background EC levels (Moore 2005). For the sake of citizen scientist repeatability, we chose to only investigate the slug method, because of the added complexity of measuring the flow rate of the salt solution for the continuous rate method.

Streamflow (Q; m^3 s^{-1}) was solved for using Eq. (2) (Rantz 1982; Moore 2005):

Eq. (2) $$Q = \frac{V}{k \sum_{i=1}^{n} (EC(t) - EC_{BG}) \Delta t}$$

where V is the total volume of tracer introduced into the stream (m^3), k is the calibration constant in centimeters per microsiemens (cm μS^{-1}), n is the number of measurements taken during the breakthrough curve (unitless), EC(t) is the EC at time t ($\mu S\ cm^{-1}$), EC_{BG} is the background EC ($\mu S\ cm^{-1}$), and Δt is the change in time between EC measurements (s).

We performed the following steps when making a salt dilution measurement:

1. Selected stream reach with turbulence to facilitate vertical and horizontal mixing
2. Determined upstream point for introducing the salt solution and a downstream point for measuring EC
    a. A rule of thumb in the literature is to separate these locations roughly 25 stream widths apart (Day 1977; Butterworth et al. 2000; Moore 2005)
3. Estimated flow rate visually by estimated width, average depth, and average velocity
4. Prepared salt solution based on the following guidelines (adapted from Moore 2005)
    a. 10000 ml of stream water for every 1 $m^3\ s^{-1}$ of estimated streamflow
    b. 1667 g of salt for every 1 $m^3\ s^{-1}$ of estimated streamflow
    c. Thoroughly mix salt and water until all salt is dissolved
    d. Following these guidelines ensured a homogenous salt solution with 1 to 6 salt to water ratio by mass
5. Performed dilution test (Moore 2004b) to determine calibration constant (k) relating changes in EC values in micro Siemens per centimeter ($\mu S\ cm^{-1}$) in the stream to relative concentration of introduced salt solution (RC)
    a. Made diluted secondary solution by mixing 500 ml of stream water and 5 ml of salt solution
    b. Measured background stream water EC (EC_{BG})
    c. Added known volume (typically 1 or 2 milliliters (ml)) of secondary solution to 500 ml of stream water in dilution cylinder
    d. Measured new dilution cylinder EC
    e. Repeated steps 5.c and 5.d until the full range of expected EC values were observed
    f. Calculated RC for each measurement point
    g. Plotted EC on the horizontal axis and RC on the vertical axis
    h. Performed linear regression
    i. Obtained k from the slope of the linear regression
6. Dumped salt solution at upstream location
7. Measured EC at downstream location during salinity breakthrough until EC returns to EC_{BG}
    a. Recorded a video of the EC meter screen at the downstream location and later digitized the values using the time from the video and the EC values from the meter
8. Solved for streamflow (Q) with Eq. (2)

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2.1.3 Bernoulli run-up

Similar to the float method, Bernoulli run-up (or Bernoulli) is based on the velocity-area principle. Total streamflow (Q; m^3 s^{-1}) was calculated with Eq. (3):

Eq. (3) $Q = \sum_{i=1}^{n} VB_i * d1_i * w_i$

where VB_i is velocity from Bernoulli run-up (m s^{-1}), $d1_i$ is depth (m), and w_i is width (m) of each sub-section (i = 1 to n). Area for each sub-section is the product of the width and the depth in the middle of each sub-section. Velocity for each sub-section (VB_i) was determined by measuring the "run-up" or change in water level on a thin meter stick from when the stick was inserted parallel and then perpendicular to the direction of flow. The basic principle is that "run-up" on a flat plate inserted perpendicular to flow is proportional to velocity based on the solution to Bernoulli's equation. Velocity (VB_i; m s^{-1}) was calculated from Bernoulli's principle with Eq. (4):

Eq. (4) $VB_i = \sqrt{2g * (d2_i - d1_i)}$

where g is the gravitational constant (m s^{-2}) and $d2_i$ and $d1_i$ are the water depths (m) when the flat plate was perpendicular and parallel to the direction of flow, respectively.

Bernoulli run-up measurements involved the following steps:

1. Selected constricted stream with elevated velocity to increase the difference between d1i and d2i
2. Divided cross section into several sub-sections (n, typically between 5 and 20)
3. For each section, measured and recorded
    a. The depth with a flat plate held perpendicular to flow (d2i or the "Run-up" depth)
    b. The depth with a flat plate held parallel to flow (d1i or the actual water depth)
    c. The width of the sub-section
4. Solved for streamflow (Q) with Eq. (3) and Eq. (4)

2.2 Reference flow

To evaluate the different citizen science flow measurement methods, a reference (or actual) flow for each site was needed. We used a SonTek FlowTracker acoustic Doppler velocimeter (ADV) to determine reference flows. The United States Geological Survey (USGS) mid-section method was used, following guidelines from USGS Water Supply Paper 2175

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(Rantz 1982), along with instrument specific recommendations from SonTek's FlowTracker manual (SonTek 2009). The FlowTracker ADV has a stated velocity measurement accuracy of within one percent (SonTek 2009). Flow measurement errors, calculated with an International Standards Organization (ISO) approach built into the FlowTracker software, are typically in the range of 3 to 10 %. Reference flow errors in this study are discuss in Section 4.5. A compilation of the measurement reports generated by the FlowTracker ADV are included as supplementary material.

2.3 Flow measurement method evaluation and analysis

We first summarized flow measurement method evaluation results in map and tabular form (Fig. 1; Table 1). Measurement ID can be used to link data between the map and table. We used scatter plots to compare reference flow (x-axis) to the three flow measurement methods evaluated (y-axis) to visualize and interpret results from each method. We fitted these points with a linear regression forced through the origin. To understand relative (normalized) errors, we calculated percent differences in relation to reference flow for each method. To better understand possible explanations for observed variability in our results, we performed a correlation analysis. For each method, we performed a Pearson's r correlation analysis (Lee Rodgers and Nicewander 1988) between the absolute value of percent difference in flow and (1) reference flow, (2) average velocity, (3) EC_{BG}, and (4) slope. Slope values were developed using elevations from the Google Earth Digital Elevation Model (DEM) obtained along the centreline of the stream alignment both 100 meters upstream and downstream of each measurement point (retrieved July 2nd, 2018). While using DEM data for slope calculations is clearly inferior to performing topographic surveys in the field, this was not possible due to lack of equipment and time; therefore, these slope data are the best available numbers.

2.4 Salt dilution calibration coefficient (k) analysis

Arguably, one of the most complicated portions of a salt dilution measurement is performing the dilution test to determine the calibration coefficient k (Moore 2004b). To determine if the dilution test needs to be repeated for each citizen science measurement, we analyzed all k values determined during this study. In addition to the mean, range, and standard deviation, we performed a Pearson's r correlation analysis (Lee Rodgers and Nicewander 1988) to see if k showed statistically significant trends with latitude, longitude, elevation, and EC_{BG}.

2.5 2.5. CS Flow campaign - pilot testing of salt dilution method

Based on the initial results from this study, S4W-Nepal developed an Open Data Kit (ODK; Anokwa et al. 2009) form for citizen scientists to perform salt dilution measurements. The general workflow was (1) selected an appropriate measurement reach with good mixing and minimal bank storage, (2) performed a simplified float measurement (i.e. only a 3 or 4 depths and velocities), (3) used the float flow estimate and EC_{BG} to provide citizen scientists recommended salt/water dose, (4) used pre-weight packets of salt (e.g. 10 g, 20 g, 50 g, 100 g, etc.) to prepare tracer solution, (5) added tracer solution to stream and recorded video of EC breakthrough curve, (6) submitted form to ODK Aggregate server, (6) digitized breakthrough curve (i.e. time and EC) in shared Google Sheet salt dilution flow calculator.

During S4W-Nepal's Citizen Science Flow (CS Flow) campaign (15th to 21st of April 2018; Fig. 6), student volunteers from Khwopa College of Engineering were recruited, trained, divided into groups by sub-watershed, and sent to the field to perform salt dilution flow measurements. In the second week, student volunteers used a salt dilution Google Sheet flow calculator to digitize collected measurement data and compute flow (see supplementary material for Excel version). Students analyzed data (third week) and finally presented oral and written summaries of their quality-controlled results. S4W-Nepal currently leverages the enthusiasm and schedule breaks in the academic calendar of young researchers to perform campaigns to improve our pre and post monsoon understanding of stone spouts (Nepali: dhunge dhara), land use, and now streamflow.

To analyze the generated streamflow data, we developed a scatter plot between flow estimates from the simplified float method (used to calculated salt dosage) and the salt dilution flow results. At locations were S4W-Nepal takes regular FlowTracker measurements, we compared the most recent S4W-Nepal observation(s) to CS Flow salt dilution measurements. Because salt dilution measurements were performed during the pre-monsoon period when precipitation is minimal, hydrographs are relatively steady with gradual recession over time as the South Asian Monsoon approaches. Therefore, we did not expect differences in time (e.g. plus or minus one month roughly) between the two measurements to greatly impact the resulting comparisons.

3 Results

3.1 Summary of evaluation measurements

We performed sets of evaluation measurements at 20 sites within the Kathmandu Valley, Nepal (Fig. 1) at elevations ranging from 1313 to 1905 meters above mean sea level. Flows evaluated ranged from 0.006 to 0.240 $m^3 s^{-1}$ (Table 1; sorted in ascending order by reference flow). Percent differences averaged 7.9, 8.2, and 25.7 % and standard deviations (std dev) of 29.1, 17.2, and 61.9 % were observed for float, salt dilution, and Bernoulli methods, respectively (Table 1). Field notes from Bernoulli flow measurements for two measurements (Msmt IDs 17041903 and 17031102) were destroyed by water damage, so flow and percent difference data were not available. Plots of EC and change in EC as a function of time for all 20 salt dilution measurements are shown in Fig. 2. Additional data for evaluation measurements is included as supplementary material.

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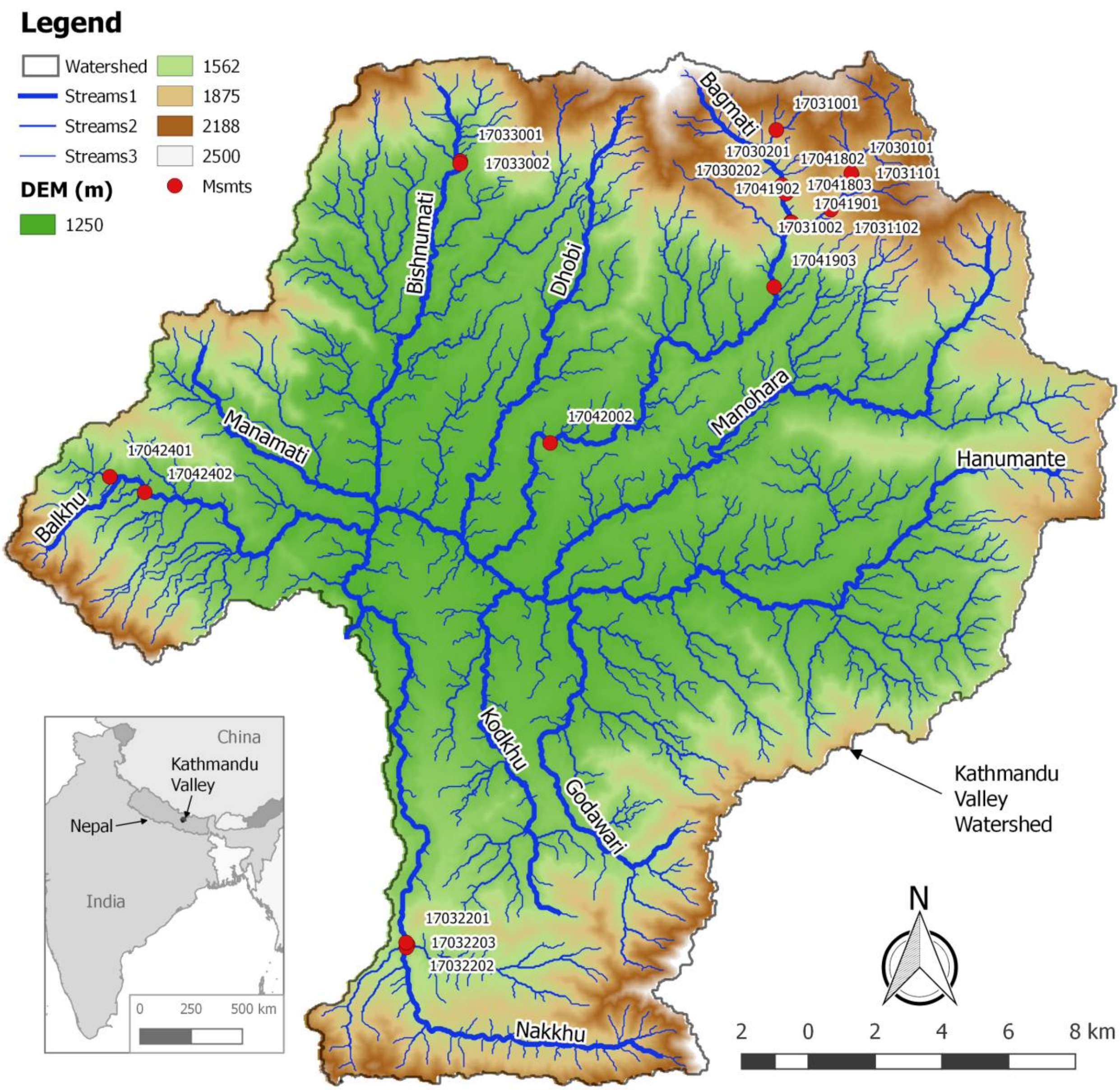

Figure 1: Map figure showing the topography (green to tan to white color gradation) of the Kathmandu Valley from a Shuttle Research Telemetry Mission (SRTM 2000) Digital Elevation Model (DEM), resulting stream network (Davids et al. 2018), and locations of flow measurements (msmts). Measurement points are labelled with measurement ID (msmt_id). Names of the ten historically perennial tributaries are shown.

Table 1: Tabular summary of measurement comparison data. Records sorted in ascending order by reference flow (Q Reference). Latitude and longitude in reference to the WGS84 datum. All flow values shown are shown in $m^3 s^{-1}$ rounded to the thousandth place. Percent differences calculated using Q Reference (FlowTracker) as the actual flow. Data summarized at the bottom with average, minimum (min), maximum (max), and standard deviation (std dev). Note that measurement ID (Msmt ID) is comprised of two digits for year, month, date, and measurement number starting at 01 each day.

Msmt ID	Latitude	Longitude	Elev-ation (m)	Q Reference (m3 s-1)	Q Float (m3 s-1)	Q Salt (m3 s-1)	Q Bernoulli (m3 s-1)	% Diff-erence Float	% Diff-erence Salt	% Diff-erence Bernoulli
17030202	27.78065	85.42426	1649	0.006	0.007	0.006	0.009	15.6	-12.5	37.5
17041802	27.78158	85.42385	1659	0.007	0.008	0.007	0.010	15.9	7.2	44.9
17031001	27.79649	85.42177	1905	0.011	0.008	0.012	0.009	-28.4	11	-19.3
17042401	27.70026	85.22077	1406	0.017	0.019	0.019	0.018	11.2	11.2	4.7
17032201	27.57487	85.31314	1482	0.018	0.020	0.024	0.019	12.4	37.3	5.1
17041901	27.77164	85.42657	1609	0.019	0.028	0.027	0.022	48.4	47.3	16.7
17033001	27.78691	85.32589	1364	0.021	0.026	0.030	0.048	27.2	43.2	132
17042402	27.69620	85.23142	1382	0.023	0.010	0.025	0.006	-59.2	5.2	-73
17041903	27.75406	85.42170	1355	0.034	0.051	0.033		51.6	-0.9	
17041902	27.77154	85.42680	1609	0.041	0.041	0.047	0.063	0.5	14.6	53.2
17030101	27.78483	85.44480	1877	0.104	0.111	0.088	0.102	6.9	-15.9	-2.6
17032203	27.57542	85.31268	1477	0.111	0.106	0.120	0.116	-4.3	8	5.1
17032202	27.57410	85.31277	1481	0.117	0.081	0.126	0.102	-30.7	8	-13.2
17033002	27.78627	85.32583	1356	0.153	0.208	0.144	0.470	36.5	-5.6	207.9
17030201	27.78156	85.42383	1659	0.155	0.248	0.176	0.161	59.3	13.1	3.5
17041803	27.78168	85.42373	1663	0.156	0.140	0.142	0.210	-10.4	-8.9	34.4
17031002	27.77932	85.42496	1653	0.159	0.183	0.155	0.228	15.2	-2.8	43.4
17031101	27.78505	85.44473	1877	0.208	0.221	0.207	0.150	6.5	-0.6	-27.8
17031102	27.77514	85.43867	1806	0.230	0.188	0.219		-18	-4.8	
17042002	27.71106	85.35432	1313	0.240	0.246	0.264	0.264	2.7	10.2	10.1
		average ->	1579	0.092	0.098	0.094	0.112	7.9	8.2	25.7
		min ->	1313	0.006	0.007	0.006	0.006	-59.2	-15.9	-73.0
		max ->	1905	0.240	0.248	0.264	0.470	59.3	47.3	207.9
		std dev ->	190	0.081	0.089	0.081	0.122	29.1	17.2	61.9

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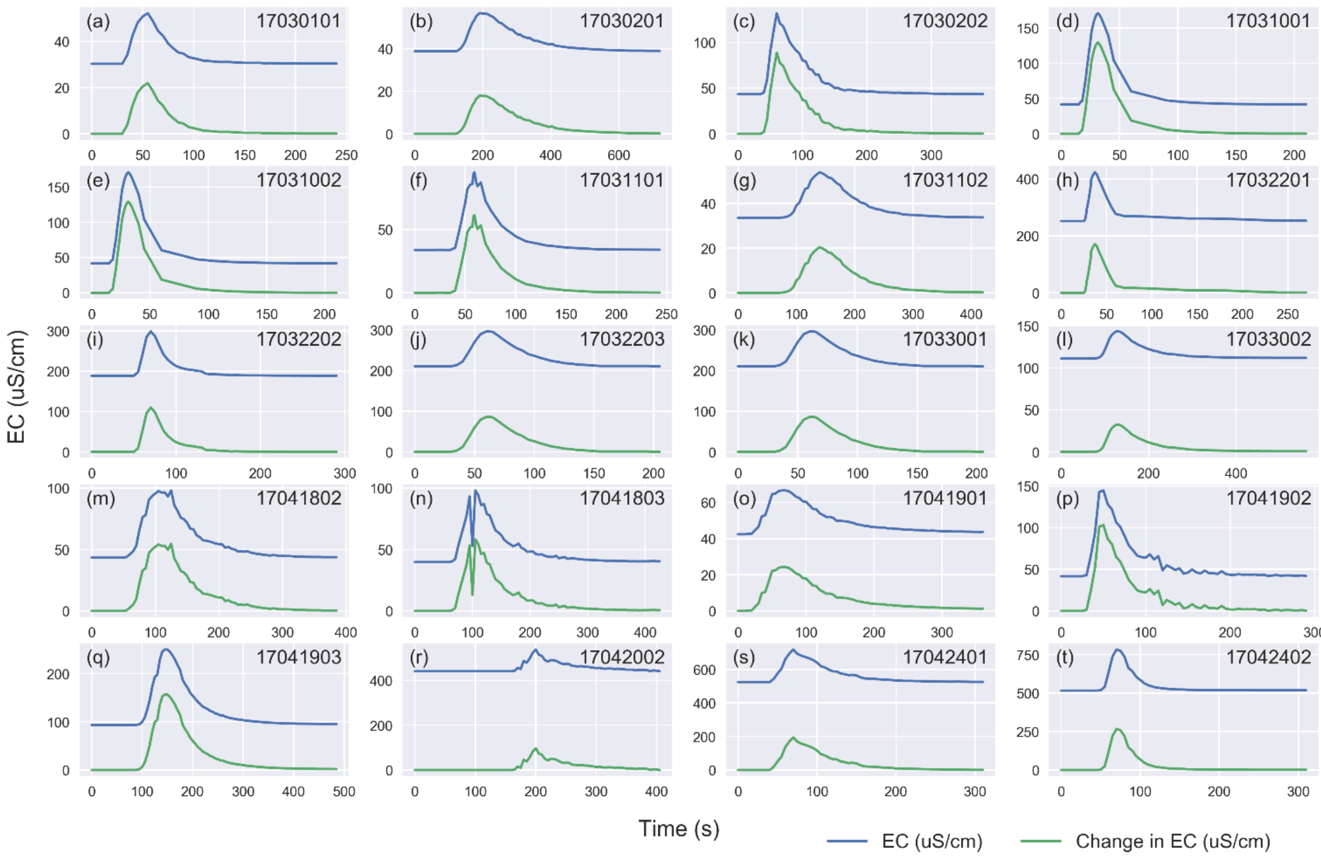

Figure 2: Plots of EC (µS cm^{-1}; blue trace) and change in EC (µS cm^{-1}; green trace) as a function of time (s) for the 20 salt dilution evaluation measurements. Measurement ID (Msmt ID; Table 1) shown at the top right of each subplot (i.e. a through t).

3.2 Flow and calibration coefficient (k) results

3.2.1 Flow scatter plots

Scatter plots between reference and observed flows with linear regressions forced through the origin had slopes of 1.05, 1.01, and 1.26 for float, salt dilution, and Bernoulli methods, respectively (Fig. 3). A slope of one represents zero systematic bias, whereas values over one represent positive bias, and values less than one represent negative bias. Therefore, for all the methods evaluated we observed different degrees of positive bias. R-squared values were 0.90, 0.98, and 0.61 for float, salt dilution, and Bernoulli methods, respectively (Fig. 3). R-squared values represent the goodness of fit between the regression and the observed data; values closer to one represent a better fit. This can also be seen by the observations for salt dilution plotting closest to the regression line, whereas float and Bernoulli points in general plot farther away from the regression line.

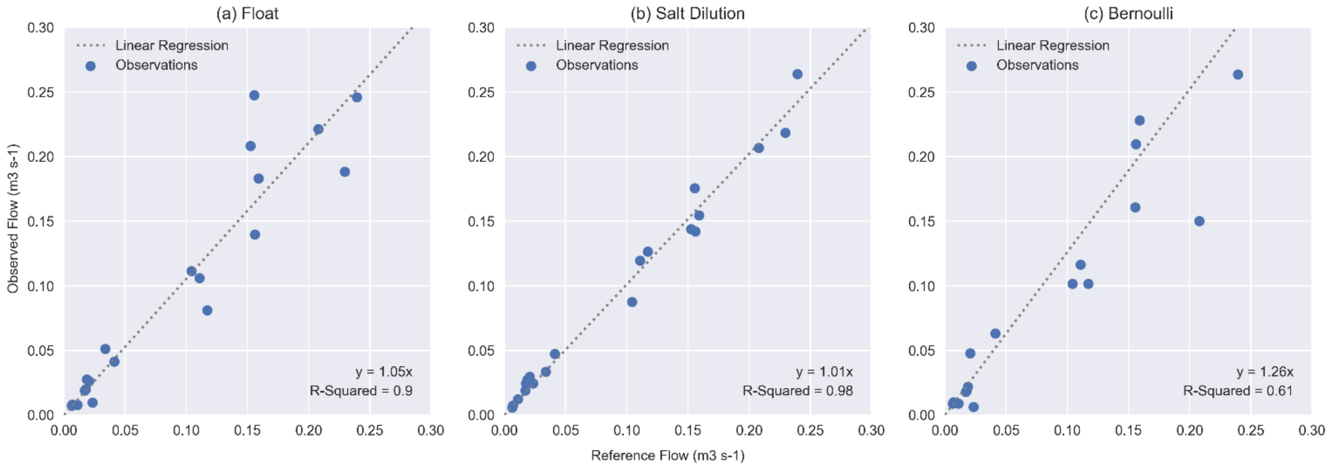

Figure 3: Scatter plots between reference flow and observed flow for (a) float, (b) salt dilution, and (c) Bernoulli. Note there is one Bernoulli measurement point (17033002) that is outside of the plot space shown (fixed from 0.0 to 0.3 for consistency). Linear regressions and r-squared values shown on the bottom right of each sub-plot.

3.2.2 Flow error correlations

We found statistically significant correlations ($n = 20$, $p = 0.1$, $r > 0.378$) between the absolute value of percent error for float and average velocity (Avg Vel; sub-plot 2; $r = -0.48$) and salt dilution percent error and reference flow (Q Ref; sub-plot 5; $r = -0.44$) (Fig. 4). In both cases, the correlation coefficient was negative, indicating an inverse relationship between the variables. No statistically significant correlations were observed between the remaining pairs of variables.

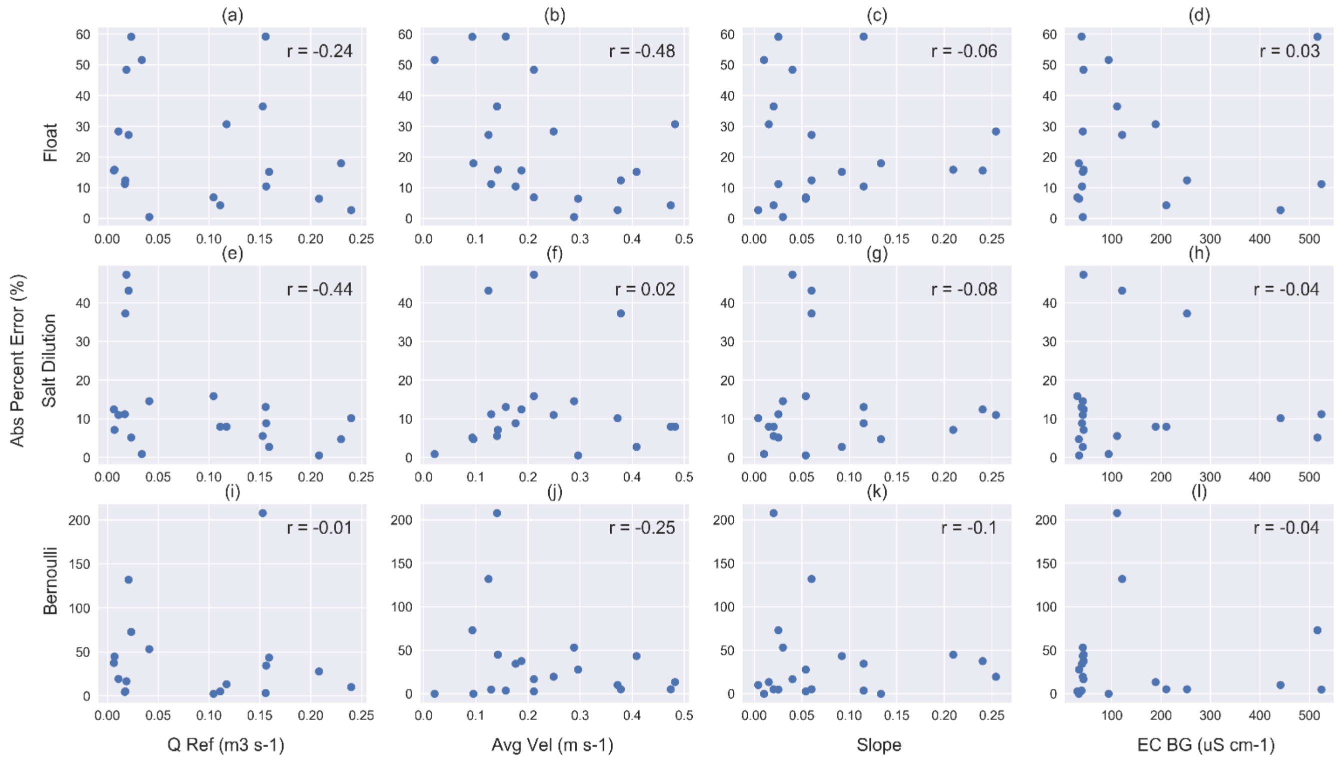

Figure 4: Scatter plots between reference flow (Q Ref; $m^3 s^{-1}$), average water velocity (Avg Vel; $m s^{-1}$), slope, and background EC (EC BG; $\mu S cm^{-1}$) and absolute value (Abs) of percent errors for float, salt dilution, and Bernoulli. Pearson's r values shown on the upper right of each subplot (i.e. a through l).

3.2.3 Salt dilution calibration coefficient (k) results

The mean calibration coefficient (k) from measurements performed in the field was 2.81 x 10^{-6} ± 2.66 x 10^{-7} (95 % confidence interval; n = 10, min = 2.57 x 10^{-6}, max = 3.05 x 10^{-6}, std dev = 1.33 x 10^{-7}). We used mean k to compute salt dilution flows for the remaining 10 measurements. We found statistically significant correlations (n = 10, p = 0.1, r > 0.549) between the calibration coefficient (k) and Longitude (r = 0.60) and Elevation (r = 0.61; Fig. 5). In both cases, the correlation coefficient was positive, indicating a direct relationship between the variables. No statistically significant correlations were observed between the remaining pairs of variables.

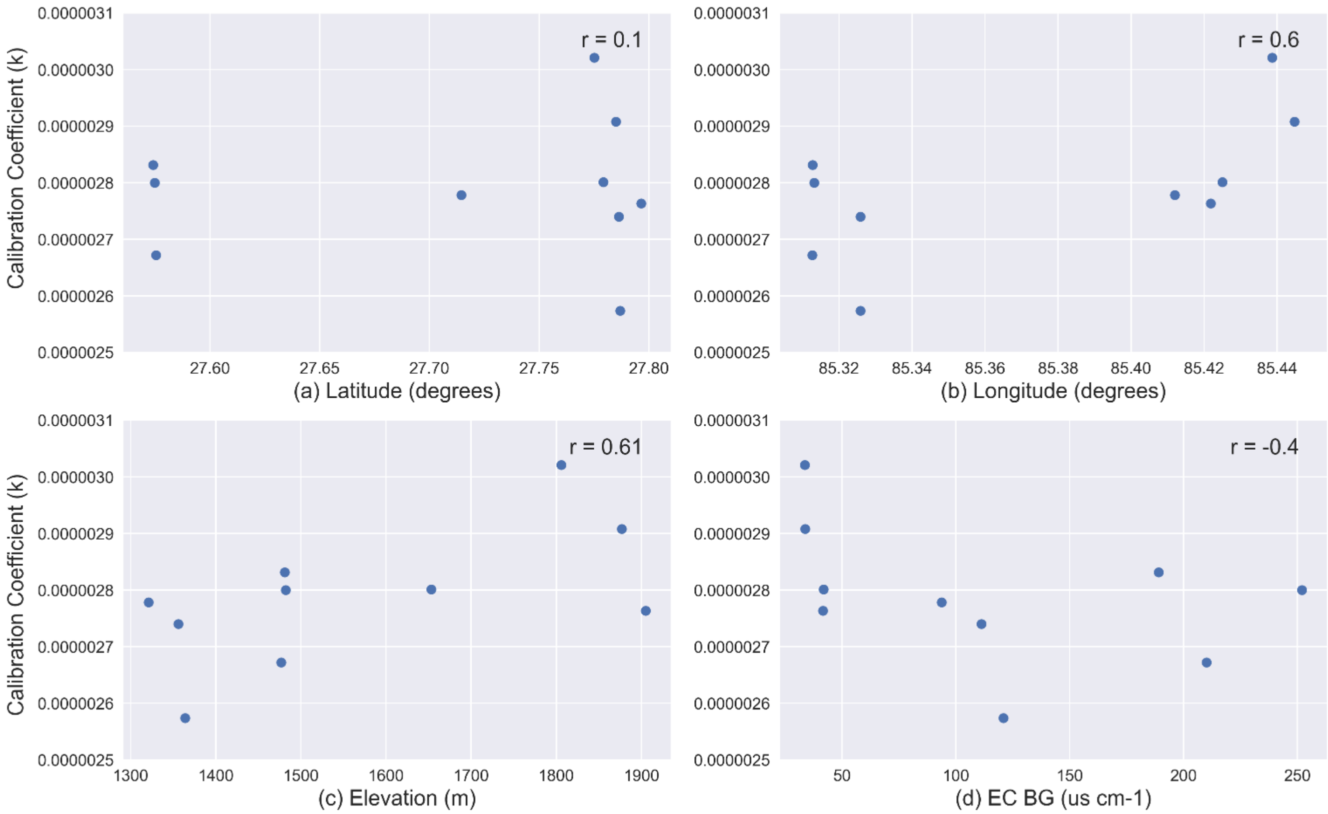

Figure 5: Scatter plots between (a) Latitude in degrees, (b) Longitude in degrees, (c) Elevation in meters above mean sea level (m), and (d) background EC in µS cm^{-1} and the salt dilution calibration coefficient (k). Pearson's r values shown on the upper right of each sub-plot.

3.3 3.3. CS Flow campaign results

From the 15th to the 21st of April 2018, 20 students from Khwopa College of Engineering in Bhaktapur, Nepal joined S4W-Nepal's CS Flow campaign. After four hours of training (i.e. two hours classroom and two hours in the field), the student volunteers performed 145 salt dilution streamflow measurements in the 10 sub-watersheds of the Kathmandu Valley (Fig. 6). Observed flows ranged from 0.0004 to 0.425 m^3 s^{-1} (a summary of the measurement data is included as supplementary material).

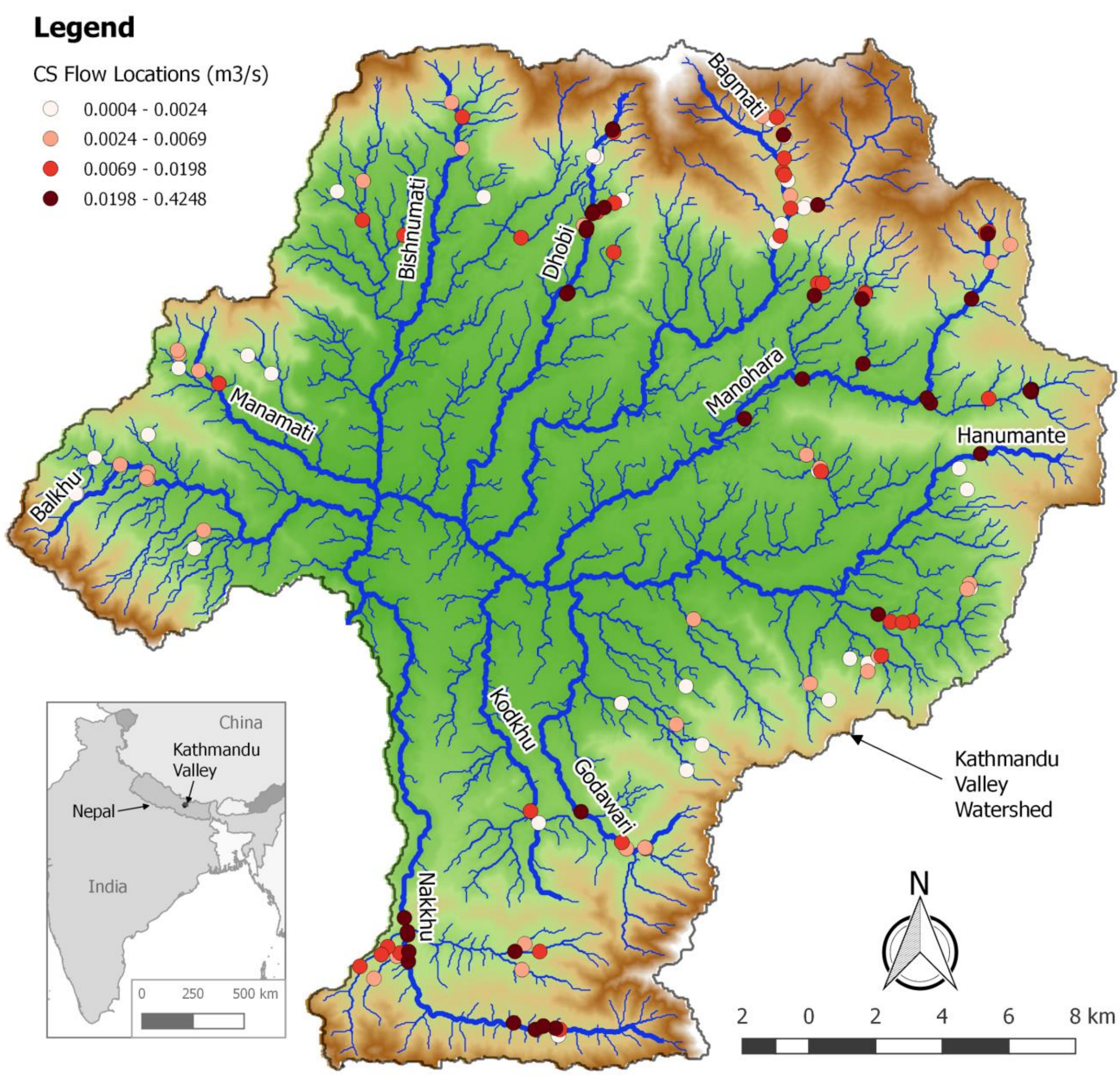

Figure 6: CS Flow Campaign measurement locations (n = 145) within the Kathmandu Valley. Circular symbol colors are graduated by observed flow rate, categorized by quartile. Larger flows (i.e. darker symbols) were observed on the mainstems (i.e. wider blue lines) of the 10 tributaries of Bagmati River in the Kathmandu Valley.

Scatter plots between flow estimates from the simplified float method (used to calculated salt dosage) and the salt dilution flow results show that systematic differences increase as the observed flow rate decreases (Fig. 7).

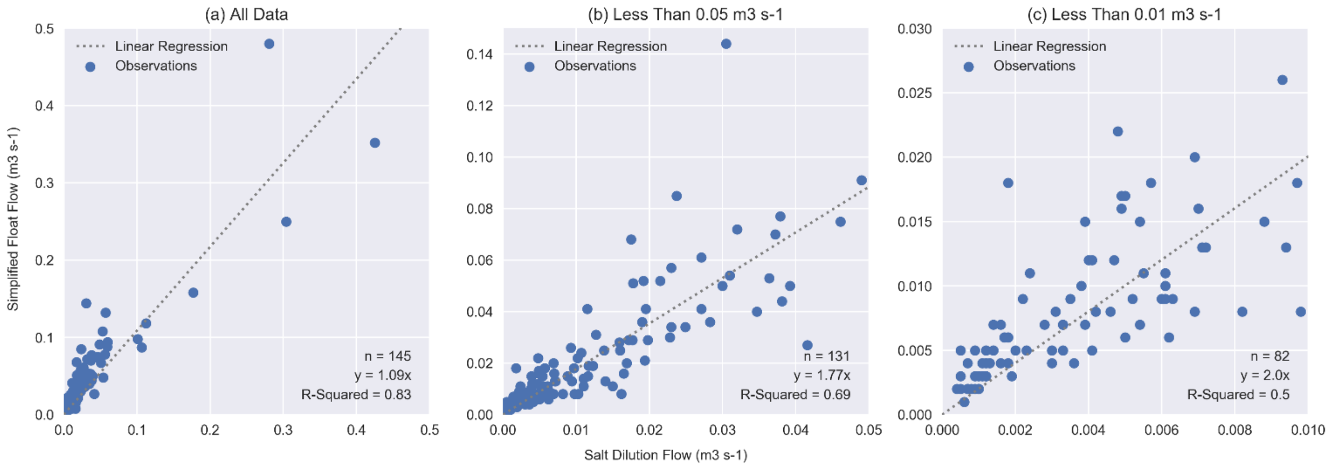

Figure 7: Scatter plots between salt dilution measurements on the horizontal axis and simplified float estimates on the vertical axis. All data are shown on subplot (a), flows below 0.05 m^3 s^{-1} are included on subplot (b), and flows below 0.01 m^3 s^{-1} are shown on subplot (c). A linear fit with corresponding r-squared values are shown. Note that the vertical axis scales for subplots (b) and (c) are fixed at three times the horizontal axis scale to ensure that all data are visible.

We identified five locations where S4W-Nepal had performed FlowTracker measurements that could be used as reference flows within roughly one month (plus or minus) of the CS Flow salt dilution measurements (Table 2). Comparable flows ranged from 0.012 and 0.111 m^3 s^{-1}. The average error between CS Flow salt dilution and S4W-Nepal FlowTracker measurements was -6.3 %, with a standard deviation of 11.5 %. Linear regression forced through the origin between reference flows and CS Flow measurements had a slope of 0.90 with an r-squared value of 0.97.

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Table 2: ***Comparison between CS Flow salt dilution and S4W-Nepal FlowTracker measurements. Five measurements were identified for evaluation. In one case (i.e. CS Flow Msmt Date 4/16/2018 10:03), a linear interpolation between two S4W-Nepal measurements (i.e. 3/15/2018 7:15 and 5/23/2018 14:23) was made because measurements for both March and May were available. Data summarized at the bottom with average, minimum (min), maximum (max), and standard deviation (std dev).***

S4W-Nepal SiteID	CS Flow Msmt Date	S4W-Nepal Msmt Date	CS Flow Salt Dilution Q (m3 s-1)	S4W-Nepal FlowTracker Reference Q (m3 s-1)	% Difference
DB02	4/16/2018 10:03	3/15/2018 7:15 and 5/23/2018 14:23	0.0529	0.0492	7.5%
BM02	4/16/2018 13:22	3/15/2018 9:49	0.0169	0.0172	-1.7%
NA02	4/18/2018 13:28	3/31/2018 4:39	0.0940	0.1110	-15.3%
BA01	4/20/2018 11:30	3/30/2018 9:24	0.0090	0.0118	-23.7%
NK03	4/18/2018 13:57	5/16/2018 12:22	0.0461	0.0454	1.5%
		average ->	0.0438	0.0469	-6.3%
		min ->	0.0090	0.0118	-23.7%
		max ->	0.0940	0.1110	7.5%
		std dev ->	0.0301	0.0353	11.5%

4 Discussion

4.1 Preferred measurement method

Based on 20 flow measurements performed in this study, we concluded that the salt dilution method will (1) provide the most accurate streamflow data (at least for the range of flows observed), and (2) will be the easiest method for citizen scientists to repeat in the field with limited amounts of training and equipment (see Section 4.4 on citizen scientist repeatability).

While all flow measurement methods evaluated had positive biases, salt dilution showed the closest agreement to the reference flow with an average over estimation of only one percent (based on the linear regression), followed by float and Bernoulli at 5 and 25 %, respectively (Fig. 3). The standard deviation for errors was 17 % for salt dilution, and 29 and 62 % for float and Bernoulli, respectively. Additionally, r-squared values indicated that salt dilution had the least amount of variance from the trend line (i.e. closest to one).

Only three salt dilution measurements (i.e. 17032201, 17041901, and 17033001) had percent differences larger than 20 %, and these were all positively biased in relatively small streams (flows between 0.018 and 0.021 $m^3 s^{-1}$). While we can't be certain, we suggest that these errors may be due hyporheic exchanges that removed some salt solution from the measurement

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reach before lateral and vertical mixing could fully occur. In other words, it is possible that some of the salt solution became "underflow" shortly after the injection point and did not return to the surface stream prior to the EC measurement location. As observed, this "removal" of salt solution would lead to a systematic overestimation of flow. If these three measurements are removed, the mean and standard deviation for salt dilution method percent differences become 2 and 9 %, respectively. These percent differences fall within the expected range of uncertainty presented in the literature for salt dilution gauging (Day 1976; USBR 2001; Moore 2004a; Herschy 2014). Excluding these three errors, and assuming errors are normally distributed, we expect that salt dilution measurements will be within roughly ±18 % (95 % confidence interval).

4.2 Measurement error correlation

In Fig. 4, three "outlier" percent errors for salt dilution measurements were seen in the middle row of sub-plots (5 through 8) as clusters of three points towards the top of each sub-plot. After removing these points, the Pearson's r value decreased to 0.26, and the correlation became statistically insignificant ($n = 20$, $p = 0.1$, $r > 0.378$). Therefore, we are cautious to conclude that error in salt dilution measurements decreases as the amount of streamflow increases. Errors in salt dilution measurements appeared to be uncorrelated with the other variables evaluated (e.g. average velocity, slope, and EC_{BG}).

The other observed statistically significant correlation was an inverse relationship between average velocity and error in float measurements. Our experience in the field validated that slow moving (and shallow) float velocity measurements were difficult to perform. The combination of turbulence and boundary layer impacts from the streambed and the overlying air mass often made floating objects on the surface travel in non-linear paths, adding uncertainty to distance and time measurements. Challenges with applying the float method in shallow depths was supported USBR (2001) and Escurra (2004), who showed that uncertainty in surface velocity coefficients (i.e. the ratio of surface velocity to actual mean velocity of the underlying water column) increased as depth decreased, especially below 0.3 m.

4.3 Salt dilution calibration coefficient (k)

Moore (2005) suggests that k depends on (1) the ratio of salt and water in the tracer solution and (2) the chemical composition of the stream water. To minimize variability in k due to changes in salt concentration, a fixed ratio of salt to water (e.g. 1 to 6 by mass) should be consistently used to prepare tracer solutions (as it was during this investigation). Significant correlations observed between k and longitude and elevation may be due to changes in water chemistry that co-vary with these independent variables. Measurements performed in the northeastern portion (i.e. higher longitude) of the Kathmandu Valley were higher in altitude. Geology in the north of the Kathmandu Valley is a mixture of weathered igneous and metamorphic parent material (e.g. gneiss, phyllite, schist, etc.). Geology surrounding measurements in the southwest of the Kathmandu Valley is dominated by sedimentary and slightly metamorphosed deposits of sand, silt, and clay (Shrestha et al. 2012). These differences in geology could impact water chemistry through water-rock interactions (Lasaga 1984) and ultimately impact k. Additional work should focus on improving our understanding of the variables affecting k. Specifically, spatial variability in k due to changes in stream water chemistry should be investigated prior to applying the salt dilution methodology described in this paper into other areas.

4.4 Citizen scientist repeatability

In this context, repeatability refers to the overall likelihood that the measurement method can be successfully repeated by citizen scientists. Along these lines, there were several practical observations in the field worth briefly discussing. While difficult to quantitatively evaluate, we offer the following qualitative observations regarding the selection of a preferred citizen science streamflow measurement method.

- **Required training** - Float and salt dilution require similar amount of training, which from our experience we estimate to be roughly four hours, involving both classroom and field time. The amount of training is strongly dependent on the background of the volunteers. Bernoulli requires additional training for how to minimize vertical movement of the metal measurement plate.
- **Cost of equipment** - All methods require a SmartPhone, measuring scale, and measuring tape. Additionally, salt dilution requires an inexpensive EC meter (e.g. $15 HoneForest Water Quality Tester), a graduated cylinder, and a bucket.
- **Number of citizen scientists required** - Teams of at least two citizen scientists are recommended for all methods; teams of three were preferred in our experience.
- **Data recording requirements** - For float and Bernoulli, depth, width, and velocity (including distance and time) data needs to be recorded at multiple locations. Salt dilution only requires some basic data entry and a video of the breakthrough curve.
- **Complexity of procedure** - Float and Bernoulli require detailed transects of the stream. Bernoulli is extremely sensitive to vertical movements in the metal measurement plate. Bernoulli is always very difficult for low velocities.
- **Enjoyability of measurement** - We found that citizen scientists generally enjoyed watching the salt dilution breakthrough curves and found them less repetitive than the tasks associated with float and Bernoulli methods. Bernoulli measurements can be frustrating when trying to keep the metal measurement plate from moving vertically, especially when there is a soft streambed.
- **Safety** - Both float and Bernoulli measurements require citizen scientists to wade through the stream. At certain flow rates this clearly poses a safety risk, especially for people who cannot swim. A clear benefit of the salt dilution

method is that everything but the simplified float estimate can be performed from the stream bank. Note that the results from the simplified float method are only used to determine the salt dosing. If the salt dosing doesn't provide a large enough change in EC to be clearly observed, the measurement can be repeated with a higher flow estimate and corresponding increase in tracer solution.

4.5 Uncertainty in reference flows

Uncertainty in measurements of reference flow (i.e. actual flow) affected uncertainty in our evaluation of the three flow measurement methods. Based on an ISO discharge uncertainty calculation within the SonTek FlowTracker software, the uncertainties in flow ranged from 2.5 to 6.0 %, with a mean of 3.7 %. Based on the literature (Rantz 1982; Harmel 2006; Herschy 2014), these uncertainties in reference flows are towards the lower end of the expected range for field measurements of streamflow. Therefore, we do not think that any systematic biases or uncertainties in our data change the results of this paper.

4.6 Reynolds number

Turbulent mixing of flow is an important aspect of salt dilution flow measurements. Reynolds number is typically used as a quantitative measure of turbulence in fluid flow. In addition to density and viscosity, fluid velocity and a characteristic length are required for calculating Reynolds number. Many of our measurements were performed in mountainous headwater streams with high slopes. To collect the most accurate reference flow measurements, however, we selected the lowest gradient stretch of the stream. The cross sections used for reference flow measurements were typically in the widest and deepest reaches of the stream to ensure the most laminar flow lines for accurate velocity and area measurements. Using velocity and characteristic length data from these reference flow measurement locations to calculate Reynolds number would not have been representative of the actual average Reynolds number of the stream reaches used for the salt dilution measurements. This is because selected stream reaches for salt dilution included steep gradients with lots of mixing, which were often either entirely upstream or downstream of reference flow locations. Therefore, we did not include Reynolds number in the correlation analysis for salt dilution.

4.7 Flow measurement methods not evaluated

We initially considered including the slope area method (USBR 2001) based on the Manning's equation for evaluation. The concept was to use a long clear flexible tube of a known length (e.g. 20 m) to measure the slope of the water surface using the principle of a water level. The tube was completely submerged and filled with water. The upstream end of the tube remained submerged and the entrance was held perpendicular to flow to ensure that only the pressure head of the stream was sensed at the tube inlet. The tube was stretched out longitudinally along the stream reach, and the downstream end of the tube was exposed to the atmosphere. The difference in water levels inside the downstream end of the tube and the stream water level immediately outside of the tube was measured. This change in head was divided by the total length of the tube to determine the slope of the water surface.

Within the first few days of field work, we concluded that this method was not suitable for piloting at the types of sites we were investigating. Because we were particularly interested in high gradient headwater streams, the primary problem was finding a stretch of stream long enough that was flowing at normal depth, without backwater and drops in the water surface caused by sudden changes in channel geometry (both longitudinally and latitudinally). An additional challenge of this method is that uncertainty in flow measurements are linearly proportional to uncertainty in estimations of the roughness coefficient (n), and n is difficult to estimate visually, especially for citizen scientists. Therefore, Manning's method was not included in this investigation. Despite our experience, we suggest that in certain settings with long straight reaches of uniform flow, Manning's may still be an appropriate citizen science flow measurement method. To simplify observations of the change in head, the Manning's method would also benefit from the installation of upstream and downstream staff gauges survey to a common datum. However, this would make the method difficult and costly to implement, and therefore less scalable.

4.8 CS Flow campaign

The CS Flow Campaign provided us with a unique opportunity to evaluate the preferred salt dilution citizen science streamflow measurement method at a larger scale. In addition to the valuable streamflow data that will help us characterize the hydrological situation in the Kathmandu Valley with greater precision, we also learned many practical lessons about how to apply citizen science based streamflow generation methods at a broader scale. Unfortunately, there was no systematic way to evaluate the accuracy of all the measurements performed. However, at the five locations were S4W-Nepal FlowTracker measurements were available, the resulting errors (μ = -6.7 %, std dev = 11.5 %; Table 2) where comparable to our initial evaluation data (μ = 8.2 %, std dev = 17.2 %; Table 1).

Linear regression forced through the origin between reference flows and salt dilution measurements had slopes of 0.90 and 1.01 with an r-squared values of 0.97 and 0.98 for CS Flow measurements and our initial evaluation measurements, respectively. Goodness of fit was similar, but while evaluation measurements had a slight positive bias (1 %), CS Flow measurements had a larger negative bias (-10 %). One possible explanation for this is that the three CS Flow comparisons that had negative percent differences (i.e. BM02, NA02, and BA01; Table 2) all used reference flows performed prior to CS Flow measurements. Since hydrographs during this season are gradually receding prior to the onset of the South Asian Monsoon, it is possible that the actual flow of the streams decreased between reference flow and CS Flow observations.

As flows decreased, we observed a progressively increasing positive bias between simplified float estimates and salt dilution measurements (Fig. 7). This finding is congruent with previous efforts to characterize the dynamic relationship between channel depth and surface velocity coefficients (USBR 2001; Escurra 2004). Average stream depths were often on the order of a few centimeters for the headwater catchments observed. Surface velocity coefficients provided by USBR (2001) range from 0.66 to 0.80 with increasing depths, but are held constant at 0.66 for depths less than 0.3 meters. Our results indicate that for flows less than 0.01 $m^3 s^{-1}$ a surface velocity coefficient of 0.5 would be more appropriate. The strength of the relationship between salt dilution and float streamflows also deteriorates as flows decrease (i.e. r-squared equals 0.83, 0.69, and 0.50 for plots 1, 2, and 3, respectively). This suggests that surface velocity coefficients are highly variable at low flow rates and correspondingly shallow depths.

5 Summary and future work

Our aim in this paper was to (1) evaluate possible citizen science streamflow measurement methods, (2) select a preferred approach, and (3) pilot test the selected method in a real-world setting. We evaluated three different approaches (i.e. float, salt dilution, and Bernoulli run-up) by performing 20 side by side comparison measurements in headwater catchments of the Kathmandu Valley. We used USGS mid-section discharge measurements from a SonTek FlowTracker acoustic Doppler velocimeter as reference flows. Evaluated flows ranged from 0.006 to 0.240 $m^3 s^{-1}$. Linear regressions forced through the origin for scatter plots with reference flows had slopes of 1.05, 1.01, and 1.26 with r-squared values of 0.90, 0.98, and 0.61, for float, salt dilution, and Bernoulli run-up methods, respectively. The salt dilution method was selected as the preferred approach based on its favourable quantitative results compared to the other methods, and other qualitative factors concerning citizen science repeatability. The approach was then pilot tested in a CS Flow Campaign, which involved 20 volunteers performing 145 measurements, ranging from 0.0004 to 0.425 $m^3 s^{-1}$, distributed among the 10 headwater catchments of the Kathmandu Valley. While there was no way to evaluate the accuracy of all 145 measurements, five of the measurements were performed in locations where USGS mid-section method discharge measurements had been performed. For these five locations, a linear regression forced through the origin between reference flows and CS Flow measurements had a slope of 0.90 with an r-squared value of 0.97.

Motivated by these promising results, future work should further evaluate the feasibility of applying citizen science based salt dilution streamflow measurements to larger areas of Nepal and beyond. Issues of how to motivate citizen scientists and young researchers (i.e. all science and engineering minded students from primary through graduate school ages) to participate in citizen science streamflow measurement efforts should receive additional attention, especially in the relatively unexplored context of citizen science in Asia. Finally, the assumption of a constant calibration coefficient (k) should be evaluated over a larger sample size covering a broader range of geological and water quality conditions.

6 Data availability

The data used in this paper are provided as supplementary material.

7 Author contribution

Jeffrey C. Davids had the initial idea for this investigation and designed the experiments in collaboration with Martine M. Rutten, Wessel David van Oyen, and Nick van de Giesen. Field work was performed by Jeffrey C. Davids, Anusha Pandey, Nischal Devkota, Wessel David van Oyen, and Rajaram Prajapati. Jeffrey C. Davids prepared the manuscript with valuable contributions from all co-authors.

8 Competing interests

The authors declare that they have no conflict of interest.

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This research was performed in the context of a larger citizen science project called SmartPhones4Water or S4W (Davids et al. 2017; Davids et al. 2018; www.SmartPhones4Water.org). S4W focuses on leveraging citizen science, mobile technology, and young researchers to improve lives by strengthening our understanding and management of water. S4W's first pilot project, S4W-Nepal, initially concentrated on the Kathmandu Valley, and is now expanding into other regions of the country and beyond. All of S4W's efforts, including the research herein, have a focus on simple field data collection methods that

can be standardized and scaled so that young researchers and citizen scientists can help fill data gaps in other data scarce regions.

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