A water-level proportional water sampler for remote areas

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1. Introduction

The analysis of water quality parameters is a key tool used in hydrological and water quality research, as well as in environmental monitoring performed by governmental institutions. Certain water quality parameters (e.g. temperature, turbidity, pH) can be measured using sensors installed on site. However, for measuring other parameters (e.g. concentrations of micropollutants or heavy metals) water samples have to be taken and analysed in the laboratory. Common sampling methods can be classified into grab sampling (the whole sample is collected at one point in time) and composite sampling (the sample consists of water collected at more than one point in time). Depending on the sampling goal and on gauge availability, composite sampling is usually performed proportional to time, water level, or discharge. Composite samples are in most cases taken by automatic water samplers that are specifically designed for sampling in the field. These water samplers have some major drawbacks: 1) They are expensive, 2) they are bulky and heavy, 3) they need power supply.

For a field campaign in a Swiss rural catchment, we aimed on measuring pesticide concentrations in surface runoff entering the inlets of a storm drainage system. These drainage inlets are only fed by surface runoff, but no other water source. During rain events, surface runoff enters through the gridded lid of the inlet and causes the water level in the inlet to rise. The water is then drained off the inlet through a pipe. After the rain event, the water level in the inlet decreases and the flow through the pipe stops. The water level then stagnates at the lower edge of the outlet pipe.

An adequate sampling method for measuring pesticide concentrations in these inlets had to fulfil several criteria: Firstly, sampling had to start with increasing water levels in the inlet and had to stop when discharge stopped. (Sampling of flowing, but not stagnating water.) Secondly, since no power supply was available at the sampling locations, sampling had to work without power supply.

We modified a pre-existing water sampler such that it fulfilled the above-mentioned criteria. In the following, we present this new sampler: An event-based water-level proportional water sampler that is cheap, easy to carry, and can be operated without power supply.

2. Sampler description

Sampler design and installation

In the following, we will first describe the design of the sampler, its installation, and then its mode of operation. The sampler consists of the following parts (see also Figure S 1 and Figure S 2).

A) Glass bottle with a volume of 1L. (DURAN Weithalsglasflasche GLS 80, Diameter: 101 mm, Height: 218 mm)
B) Screw cap (DURAN GLS80) that was customized with two openings. For this, two holes were drilled into the top of the screw cap. These holes were equipped with one waterproof thread each.
C) Bent metal tube (inner diameter: 4 mm).

D) Plastic tubing (FESTO PUN 6x1-BL, inner diameter: 4 mm, length: 2 m)
E) Needle valve (Bronkhorst precision valve, NV-004-HR). The valve coefficient K_V (which determines the flow through the valve at a given pressure) can be adjusted between 0 and 10^{-3} m^3 hr^{-1} $bar^{-1/2}$ using an adjustment stem.

Before installing the sampler, we screwed the cap tightly on the glass bottle, such that gas and water exchange between the bottle and its environment could only occur through either the plastic tubing or the metal tube. Afterwards, we installed the sampler in the stormwater drainage inlet as shown in Figure 1 (and Figure S 3). We attached the sampler firmly using a clamp mounted at the inlet wall. The border of the glass bottle was located slightly higher than the level of the stagnant water (i.e. in most cases the level of the outlet pipe lower edge). This ensured that no water could enter the bottle during dry periods. The needle valve was installed outside of the stormwater drainage inlet at a dry spot.

Additionally, we installed a water level sensor in the stormwater drainage inlet. From water level data, we could estimate the amount of water sampled at each time point (see section "calculation of sampled water volume").

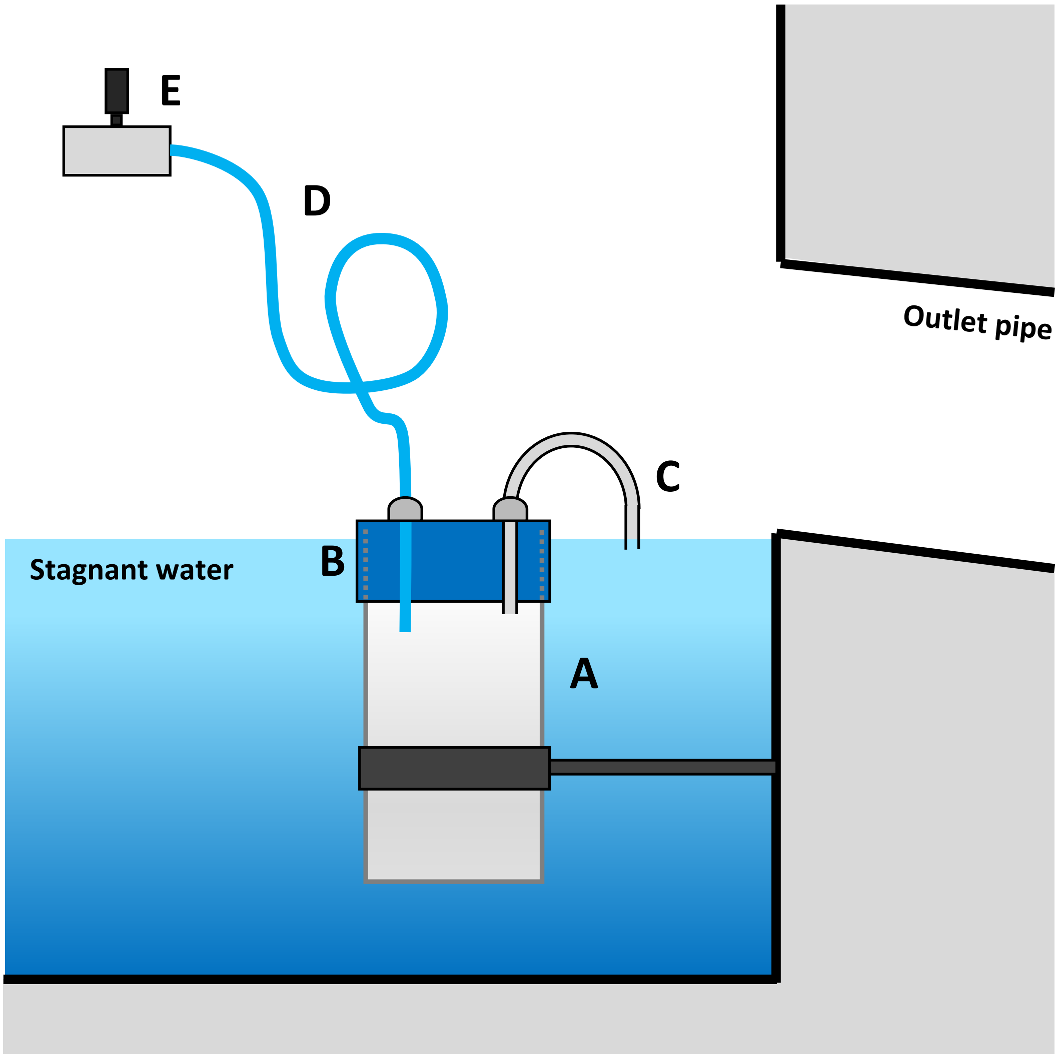

Figure 1: Installation of the water-level proportional sampler in a stormwater drainage inlet during dry weather. A: Glass bottle, B: Screw cap, C: Metal tube, D: Plastic tubing, E: Needle valve

Operation principle

During rain events, surface runoff enters the stormwater drainage inlet through the gridded lid, falls into the stagnant water, inducing a rise of the water level in the inlet (see Figure 2 and Figure S 4). With rising water level, water begins to flow through the outlet pipe. Once the bent metal tube is fully submerged, water also flows into the sampling bottle through the metal tube. The air in the bottle is compressed and pressed out of the bottle through the needle valve. Consequently, an equilibrium between the inflowing water volume (Q_{in}), the outflowing air volume (Q_{out}), and the compression of air and water is established. If the compression equals zero, the volume of water flowing into the bottle is equal to the volume of air flowing out of the bottle. The sampling stops either when the water level drops below the water inlet, or when the sampling bottle is full.

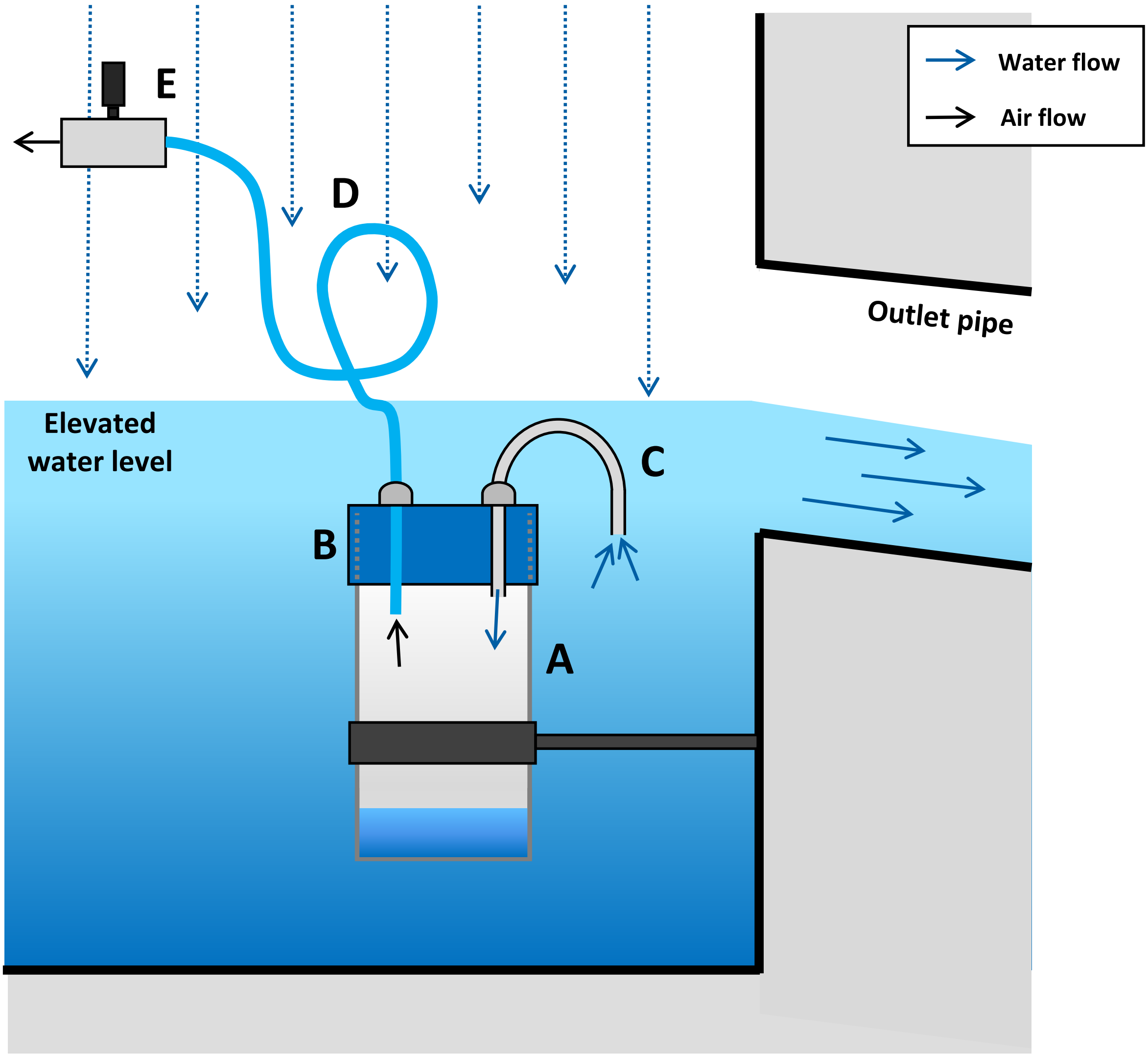

Figure 2: Water-level proportional sampler in a stormwater drainage inlet during a rain event. A: Glass bottle, B: Screw cap, C: Metal tube, D: Plastic tubing, E: Needle valve

Calculation of sampled water volume

In the following, we will describe how the operation principle can be described mathematically and how the sampled water volume can be estimated from water level data.

The volume in the sampling bottle is constant. Accordingly, the volume balance can be described by equation 1. It consists of the inflowing water volume (Q_{in}), the outflowing air volume (Q_{out}), and the change of air volume (V_a) and water volume (V_w) in the bottle. The air and water volume in the bottle can change due to compression (and decompression) caused by changes in pressure (p) or temperature (T). Pressure changes are induced by changing water levels. Temperature changes are induced by cooling or heating by the water around the bottle or entering the bottle. Since changes in pressure and temperature have a much larger influence on air compression than on water compression, equation 1 can be simplified to equation 2.

$$(1)\quad \frac{\partial V}{\partial t} = Q_{in}(t) - Q_{out}(t) + \frac{\partial V_W}{\partial t}(T) + \frac{\partial V_W}{\partial t}(p) + \frac{\partial V_a}{\partial t}(T) + \frac{\partial V_a}{\partial t}(p) = 0$$

$$(2)\quad Q_{in}(t) - Q_{out}(t) + \frac{\partial V_a}{\partial t}(T) + \frac{\partial V_a}{\partial t}(p) \cong 0$$

V_a:	Air volume in the bottle (mL)
V_w:	Water volume in the bottle (mL)
Q_{in} (t):	Inflowing water volume (mL min^{-1}) at time t
Q_{out} (t):	Outflowing water volume (mL min^{-1}) at time t
T:	Temperature in the bottle (K)
p:	Pressure in the bottle (bar)

We assume that after an initial amount of water inflow into the bottle (initial sampling volume, $V_{W,0}$), the air compression in the bottle due to pressure and temperature changes can be neglected. Accordingly, for time points t > 0, Q_{in} can be set equal to Q_{out}. The outflowing air volume (Q_{out}) is limited by the characteristics of the needle valve and can be described by the equation for flow through a valve. Accordingly, Q_{in} can be written as shown in equation 3.

$$(3)\quad Q_{in}(t) \cong Q_{out}(t) = K_V \cdot \sqrt{\frac{\Delta p(t)}{\rho_{air,rel}}} \qquad | \, t > 0$$

K_V:	Valve coefficient (mL min^{-1} $bar^{-1/2}$)
Δp (t):	Pressure difference (bar) at time t
$\rho_{air,rel}$:	Relative air density = $\rho_{air} \cdot 10^{-3}$ kg^{-1} m^3 (-)

Assuming that the difference between the air pressure at location C (i.e. inlet of the metal tube) and location E (i.e. the valve outlet) is small, the pressure difference Δp can be expressed as shown in equation 4.

$$(4)\quad \Delta p(t) = p_C(t) - p_E(t) = \left(h_{w,C}(t) + p_{a,C}(t)\right) - p_{a,E}(t) \cong h_{w,C}(t)$$

p_C (t):	Pressure at location C (i.e. inlet of the metal tube) (bar) at time t
p_E (t):	Pressure at location E (i.e. the valve outlet) (bar) at time t
$h_{w,C}$ (t):	Water level at location C (bar) at time t
$p_{a,C}$ (t):	Air pressure at location C (bar) at time t
$p_{a,E}$ (t):	Air pressure at location E (bar) at time t

Combining equation 3 and 4 results in equation 5, describing the inflowing water volume (Q_{in}). The inflowing water volume is directly proportional to the square root of the water level.

$$(5) \quad Q_{in}(t) = K_V \cdot \sqrt{\frac{h_{w,C}(t)}{\rho_{air,rel}}} \qquad | \, t > 0$$

K_V: Valve coefficient (mL min^{-1} $m_{H2O}^{-1/2}$)
$h_{w,C}$ (t): Water level at location C (m_{H2O}) at time t
$\rho_{air,rel}$: Relative air density = $\rho_{air} \cdot 10^{-3}$ kg^{-1} m^3 (-)

The total amount of water sampled in the bottle (V_B) can be calculated by integrating Q_{in} over the time sampled (equation 6). However, since this integral also includes time point 0, the initial sampling volume ($V_{W,0}$) has to be added to the equation.

$$(6) \quad V_w(t) = \int_0^t Q_{in}(t)dt + V_{W,0} = \int_0^t K_V \sqrt{\frac{h_{w,C}(t)}{\rho_{air,rel}}} dt + V_{w,0}$$

V_w (t): Total amount of water sampled (mL) at time t
Q_{in} (t): Inflowing water volume (mL min^{-1}) at time t
$V_{w,0}$: Initial sampling volume (mL)
K_V: Valve coefficient (mL min^{-1} $m_{H2O}^{-1/2}$)
$h_{w,C}$ (t): Water level at location C (m_{H2O}) at time t
$\rho_{air,rel}$: Relative air density = $\rho_{air} \cdot 10^{-3}$ kg^{-1} m^3 (-) at time t

The initial sampling volume ($V_{W,0}$) corresponds to the difference between the air volume in the bottle before the start of the event ($V_{air,pre}$) and the air volume in the bottle directly after event start when the air in the bottle is compressed ($V_{air,0}$). Using the combined gas law (equation 7), the initial sampling volume can be determined as shown in equation 8.

$$(7) \quad \frac{p_{C,0} \cdot V_{air,0}}{T_{air,0}} = \frac{p_{C,pre} \cdot V_{air,pre}}{T_{air,pre}}$$

$$(8) \quad V_{w,0} = V_{air,pre} - V_{air,0} = V_{air,pre} \left(1 - \frac{p_{C,pre}}{T_{air,pre}} \frac{T_{air,0}}{p_{C,0}}\right)$$

$p_{C,pre}$: Pressure at location C before event start (m_{H2O})
$p_{C,0}$: Pressure at location C directly after event start (m_{H2O})
$V_{air,pre}$: Air volume in the bottle before event start (mL)
$V_{air,0}$: Air volume in the bottle directly after event start (mL)
$V_{w,0}$: Initial sampling volume (mL)
$T_{air,pre}$: Air temperature in the bottle before event start (K)
$T_{air,0}$: Air temperature in the bottle directly after event start (K)

The pressure at location C before event start equals the atmospheric pressure. The pressure at location C after event start equals the sum of the atmospheric pressure and the water level at location C. We if we additionally assume that the air temperature in the bottle after event start equals the water temperature in and around the bottle, we can rewrite the equation as shown in equation 9.

$$(9) \quad V_{w,0} \cong V_{air,pre}\left(1 - \frac{p_{air,C}}{T_{air,pre}}\frac{T_{w,0}}{h_{w,C}(0) + p_{air,C}}\right)$$

$V_{w,0}$:	Initial sampling volume (mL)
$V_{air,pre}$:	Air volume in the bottle before event start (mL)
$p_{air,C}$:	Air pressure at location C (m_{H2O}) at time 0
$h_{w,C}$ (0):	Water level at location C (bar) at time 0
$T_{air,pre}$:	Air temperature in the bottle before event start (K)
$T_{w,0}$:	Water temperature directly after event start (K)

Valve coefficient calibration

In the following, we will explain how the needle valve was calibrated during the field campaign. Before calibrating the valve coefficient of the needle valve, we had to choose a proper valve coefficient. For this, we had to compromise between two targets. For small events (e.g. water level above metal tube inlet: 1 cm, duration: 20 min), the valve coefficient had to be large enough such that sufficient sample is taken for the chemical analysis. However, for large events (e.g. water level above metal tube inlet: 6 cm, duration: 2 hours), the valve coefficient had to be small enough such that the composite sample integrates as much of the event duration as possible, before the bottle is full.

Using the adjustment stem of the needle valve, we calibrated the valve to the desired valve coefficient (K_V). Since we did not know which position of the adjustment stem corresponds to which valve coefficient, we determined the position in an iterative procedure:

1. We selected a random position of the needle valve adjustment stem.
2. a) We submerged the bottle at a constant water level for a certain duration. Afterwards, we measured the amount of water sampled.
   b) We submerged the bottle again at the same water level, but for a different duration. Afterwards, we measured the amount of water sampled.
3. We calculated the valve coefficient using equation 5.
   (Note: In equation 5, the valve coefficient (K_V) and the initial sampling volume ($V_{W,0}$) are unknown. Therefore, two measurements (a and b) were needed to calculate the valve coefficient.)
4. We changed the adjustment stem position slightly in the direction of the desired value and returned to step 2.

We stopped the iterative procedure, as soon as we approximately reached the desired valve coefficient.

In an additional step, we determined the uncertainty of the valve coefficient. For this, we submerged four sampling bottles (A, B, C, and D) with different calibrated valve coefficients multiple times for different submersion durations at different water depths. Afterwards, we measured the sampled volumes and determined the uncertainty of the valve coefficients.

3. Results & Discussion

Above, we presented the design and operation principle of our sampler. We showed that except for an initial sampling volume at event start, the amount of water sampled is approximately proportional to the square root of the water level. In the following, we will show results on the uncertainty of the valve coefficients (and the corresponding sampling volumes) and will discuss sources of potential failure during operation, as well as advantages and disadvantages of the sampler.

Sampling uncertainty

The valve coefficients determined for the four sampling bottles can be found in Table S1 to S4 in the appendix. For the four sampling bottles, the relative standard deviations of the valve coefficients (and accordingly of the corresponding sampling volumes) equalled 9.4 %, 8.0 %, 6.8 %, and 17.4 %. Considering the simple sampler design, we rate these uncertainties as small and appropriate for our purpose.

However, the valve coefficient uncertainties reported above are only valid under the prerequisite of a regular operation of the sampler and the needle valve. This requires that the sampler is installed properly (as described in the section “sampler design and installation”) and that the metal tube inlet, the plastic tubing, and the needle valve are free from clogging. During the field campaign, in some occasions, moisture could enter the needle valve, clogging the valve and leading to a strong sampling rate reduction. It is therefore important to keep the needle valve dry. This can for example be ensured by putting the needle valve into a box together with silica gel, protecting it from rainfall and air moisture.

During hot temperatures in summer, we observed an additional potential error source. When the sampler was installed in the storm drainage inlet, the air in the bottle was cooled down immediately by the water around the bottle, causing an air volume reduction and hence a lower air pressure in the bottle compared to the ambient atmospheric air pressure (see also equation 6). This pressure difference could not be balanced out fast enough through the needle valve. Consequently, although the water level was below the border of the glass bottle, substantial amounts of water were sucked into the bottle through the metal tube. We therefore recommend pre-cooling of the open bottle before screwing the cap and installing the bottle in the storm drainage inlet.

Advantages & disadvantages of the sampler

The water sampler has the advantages of being cheap, easy to carry, and can be operated without power supply. Depending on the sampling location and project goals, this can be a large advantage compared to other types of samplers. Considering the simple construction principle, the water-level dependent sampling rates are quite reliable.

The sampler, however, also has disadvantages. Some of them are listed in the following:

1. *The sampling rate is proportional to the square root of the water level:* For load calculations, a proportionality to the discharge would be preferable.
2. *The sampler provides only one composite sample per event:* Differences in concentration at different points in time cannot be monitored with this setup.
3. *The sampler does not provide feedback:* In contrast to some automatic samplers, the sampler presented here does not provide any feedback on sampling state (e.g. bottle is full) or on failures (e.g. clogging of the sampler). This however would be a large advantage for seamless sampling.

Supporting information

Table S 1: Sampling rates measured for different water levels and sampling durations for valve A. These measurements were used to calculate the valve coefficient uncertainty of valve A.

Water level (cm)	Sampling duration (min)	$V_{w,0}$ (mL)	$V_{w,tot}$ (mL)	$V_{w,tot}$ - $V_{w,0}$ (mL)	Q_{in} (ml/min)	K_v (m^3/hr)
4	11	14.0	65.0	51.0	4.6	1.5E-04
1	15	10.0	50.0	40.0	2.7	1.8E-04
2	12	10.0	50.0	40.0	3.3	1.6E-04
2	12	10.0	60.0	50.0	4.2	2.0E-04
2	12	10.0	60.0	50.0	4.2	2.0E-04
4	20	14.0	115.0	101.0	5.1	1.7E-04
2	12	10.0	60.0	50.0	4.2	2.0E-04
5	15	15.8	110.0	94.2	6.3	1.9E-04
5	30	15.8	197.3	181.6	6.1	1.8E-04
5	45	15.8	230.2	214.4	4.8	1.4E-04
5	60	15.8	344.5	328.8	5.5	1.6E-04
10	15	21.5	157.0	135.5	9.0	1.9E-04
10	30	21.5	284.8	263.3	8.8	1.8E-04
10	45	21.5	395.8	374.3	8.3	1.8E-04
10	60	21.5	478.8	457.3	7.6	1.6E-04
					μ	**1.8E-04**
					σ	**1.7E-05**
					σ/μ	**9.4%**

Table S 2: Sampling rates measured for different water levels and sampling durations for valve B. These measurements were used to calculate the valve coefficient uncertainty of valve B.

Water level (cm)	Sampling duration (min)	$V_{w,0}$ (mL)	$V_{w,tot}$ (mL)	$V_{w,tot}$ - $V_{w,0}$ (mL)	Q_{in} (ml/min)	K_v (m^3/hr)
4	11	14	85.0	71.0	6.5	2.2E-04
2	10	10.0	50.0	40.0	4.0	2.2E-04
1	15	10.0	65.0	55.0	3.7	2.4E-04
10	15	22.5	173.6	151.1	10.1	2.1E-04
10	30	22.5	304.0	281.5	9.4	2.0E-04
10	45	22.5	432.2	409.6	9.1	1.9E-04
10	60	22.53	578.7	556.1	9.3	2.0E-04
					μ	**2.1E-04**
					σ	**1.7E-05**
					σ/μ	**8.0%**

Table S 3: Sampling rates measured for different water levels and sampling durations for valve C. These measurements were used to calculate the valve coefficient uncertainty of valve C.

Water level (cm)	Sampling duration (min)	$V_{w,0}$ (mL)	$V_{w,tot}$ (mL)	$V_{w,tot}$ - $V_{w,0}$ (mL)	Q_{in} (ml/min)	K_v (m^3/hr)
4	11	14.0	100.0	86.0	7.8	2.6E-04
1	15	10.0	80.0	70.0	4.7	3.1E-04
2	12	10.0	80.0	70.0	5.8	2.7E-04
2	12	10.0	80.0	70.0	5.8	2.7E-04
2	12	10.0	80.0	70.0	5.8	2.7E-04
2	12	10.0	75.0	65.0	5.4	2.6E-04
20	15	35.1	294.1	259.0	17.3	2.6E-04
20	30	35.1	532.9	497.7	16.6	2.5E-04
20	45	35.1	804.0	768.9	17.1	2.5E-04
20	60	35.1	1032.9	997.7	16.6	2.5E-04
					μ	**2.7E-04**
					σ	**1.8E-05**
					σ/μ	**6.8%**

Table S 4: Sampling rates measured for different water levels and sampling durations for valve D. These measurements were used to calculate the valve coefficient uncertainty of valve D.

Water level (cm)	Sampling duration (min)	$V_{w,0}$ (mL)	$V_{w,tot}$ (mL)	$V_{w,tot}$ - $V_{w,0}$ (mL)	Q_{in} (ml/min)	K_v (m^3/hr)
4	11	14.0	95.0	81.0	7.4	2.5E-04
1	15	10.0	65.0	55.0	3.7	2.4E-04
5	15	15.0	109.0	94.0	6.3	1.9E-04
5	30	15.0	183.3	168.3	5.6	1.7E-04
5	45	15.0	237.8	222.8	5.0	1.5E-04
5	60	15.0	358.1	343.1	5.7	1.7E-04
20	15	32.9	290.1	257.2	17.1	2.6E-04
20	30	32.9	412.0	379.1	12.6	1.9E-04
20	45	32.9	618.8	586.0	13.0	1.94E-04
20	60	32.9	843.9	811.0	13.5	2.01E-04
					μ	**2.0E-04**
					σ	**3.5E-05**
					σ/μ	**17.4%**

Figure S 1: Picture of an empty sampling glass bottle, including screw cap, waterproof threads, metal tube, and plastic tubing.

Figure S 2: Picture of the needle valve used (Bronkhorst precision valve, NV-004-HR).

Figure S 3: Installation of a water-level proportional sampler in a storm drainage inlet.

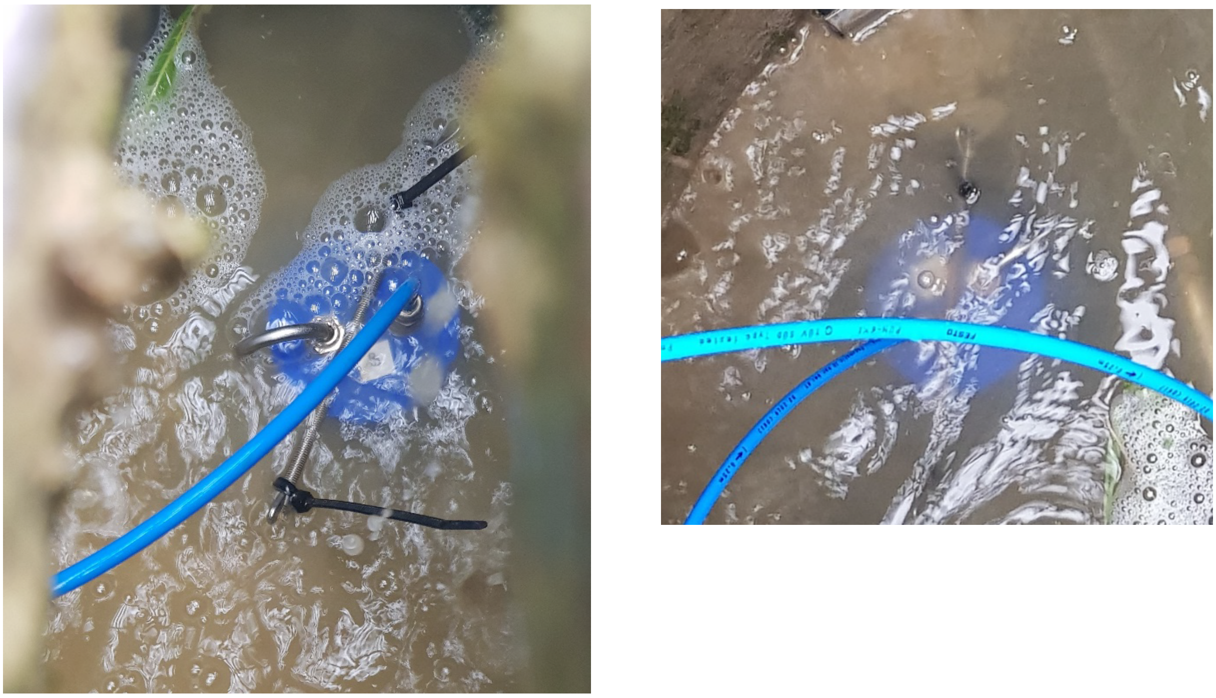

Figure S 4: A water level proportional sampler at the start of a rain event (left) and during a rain event (right).