Climatological and hydrologic field course

Discharge measurements

MSc course: Climatological and hydrologic field course - FS2023
Lecturers: Dominik Michel, Martin Hirschi, Michael Rösch,
Killian Brennan, Marius Egli and Felix Jäger

Responsible for discharge experiments: Felix Jäger (felix.jaeger@env.ethz.ch)

1 Introduction

Discharge (or surface runoff Q_s) refers to the horizontal water flow occurring at the surface in rivers and streams. It does not include the groundwater flow (or subsurface runoff Q_g). Since discharge is only defined in streams or rivers, water balance calculations are often performed for the catchment area upstream of the discharge measurement site, toward which it is often assumed to drain entirely. This means that the hydrological boundaries of the catchment are assumed to correspond to the topographic watershed boundaries. In reality, these can be crossed by the groundwater flow, making this assumption not perfectly valid. Moreover, the catchment boundaries might also change with time or wetness. During the field course we only measure the surface runoff.
Surface runoff can be caused by many processes. Under normal conditions, only subsurface flow contributes to stream flow once it reaches the surface. However, topography, as well as soil characteristics, can also determine the amount of discharge. For example, the hydraulic conductivity – which depends strongly on the soil wetness - controls how easily the precipitated water can percolate vertically into the ground. Depending on this property, during intense precipitation, water might be unable to infiltrate into the soil, leading to infiltration-excess runoff. Moreover, after prolonged rainfalls, soils might become saturated, and the remaining precipitation can lead to saturation-excess runoff. The type of vegetation can influence the physical properties of a soil as well, and experiments of land-cover changes at the catchment-scale were found to influence the surface discharge.
Total (surface + subsurface) runoff Q is often expressed in volume of water per unit of time (m^3/s or l/s). Alternatively, it can be expressed in equivalent water depth at the catchment scale, dividing Q by the catchment area. This is useful, or even essential, in water balance studies where other fluxes (e.g. precipitation or evapotranspiration) already have the dimension Length/Time (e.g. mm/d). Discharge can then be formulated as a function of other surface water fluxes through the surface water balance equation:

$$Q = Q_s + Q_g = P - E - \frac{dS}{dt} \tag{1}$$

Here, P is precipitation, E is evapotranspiration, and $\frac{dS}{dt}$ stands for the temporal change in soil moisture content. All terms are expressed in m3/s or in mm/d. Compared to the other terms in the equation, Q_s is the only one which is representative for the whole catchment area upstream of the discharge measurement site. Note that on climatic (multi-annual) timescales, $\frac{dS}{dt}$ is often considered to be zero, meaning that total runoff is equal to the difference between precipitation and evapotranspiration.

2 Measurement methods

a) Bucket method

If one finds a spot where it is possible to capture all the water from the streamflow (for example at a spillway), using a stopwatch and a bucket. Depending in the discharge, it might be decided to either measure the time that it takes to fill the bucket, or measure the volume of water collected in a predefined time span.

Further tasks and questions Do not only try this at the two creeks but also note down the advantages and limitations of this method.

b) Water height relationships

An often-used technique to quickly establish the discharge, is to take advantage of the fact that water height is directly related to stream morphology and discharge. By introducing structures into the river (such as weirs), the morphology is fixed, and a relationship can be determined using any of the other methods presented here. Once this relationship is established, a simple water height measurement suffices to determine the discharge.
This technique is often used for continuous (automated) discharge measurements. A pressure transducers or ultrasonic depth sensor is installed next to point where the relationship was established. These devices are completely automatic and log water height at high temporal resolution.
The relationships were defined for both the Huwilerbach (Appendix I) and the Upper Rietholzbach (Eq. 2, v [m/s] is stream velocity, d [cm] is water depth as indicated by the scale).

$$v = 0.0198\ (d - 17.7)^{1.3597} \tag{2}$$

Multiplied with the cross-sectional area, the discharge can be determined.

Further tasks and questions Can you think of disadvantages of this method and its implementation at Rietholzbach? What about discharge extremes, i.e. periods of very little or very high discharge?

c) Float method

This method can be used to get a very rough estimate of the runoff. With a floating object the surface velocity of the river is measured. The mean river velocity can then be approximated by

$$v_{mean} = 0.85\ v_{surface}\ , \tag{3}$$

where v_{mean} [m/s] is the mean stream velocity and $v_{surface}$ [m/s] is the flow velocity at the surface.

Further tasks and questions Try this method using a tracer swimming at the surface. Multiplied with the cross-sectional area, the discharge can be determined. Discuss how estimates from surface velocity measurements could be made more accurate.

d) Manning's equation

This method allows an approximate estimation of runoff without performing any velocity or runoff measurements. The empirical "Manning's equation" assumes that there is a relation between the river geometry and velocity. Manning's equation states

$$v = \frac{1}{n} R^{2/3} S^{1/2}, \tag{4}$$

where n [s/m$^{1/3}$] is Manning's roughness coefficient, $R = A/P_w$ is the hydraulic radius, A [m^2] the cross-sectional area of the flow , P_w [m] the wetted perimeter (see Fig. 1) and S [ ] the fractional slope of the water surface. For the wetted perimeter, a common approximation is

$$P_w \approx 2d_{max} + \sum_{i=1}^{n} w_i \ , \tag{5}$$

a rectangular shape. The result from Manning's equation, again, needs to be multiplied by the cross-sectional area. The advantage of this method is that it is very simple and fast to use. The disadvantage lies in the empirical nature of the equation 4, so that it should only be used to get an idea of the magnitude of runoff.

Further tasks and questions Try to think of situations, where this method might be the only one you can easily apply. Is there one or do we always have better methods at hand?

e) Cross-sectional velocity measurement

Discharge is obtained by calculating the integral of the stream velocity over the cross-section area of the flow A, where v is measured perpendicular to the cross-section.

$$Q = \int v \; dA \approx \sum_{i=1}^{n} v_i A_i \tag{6}$$

The velocity can be measured in discrete intervals along the cross-section by means of a current-meter or a dipping bar. The areas A_i corresponding to the velocities v_i can be determined with the help of an approximation of the river bed as linear interpolation of the depths d_{i-1} and d_i distanced by the width w_i

$$A_i = w_i \frac{d_{i-1} + d_i}{2} \ . \tag{7}$$

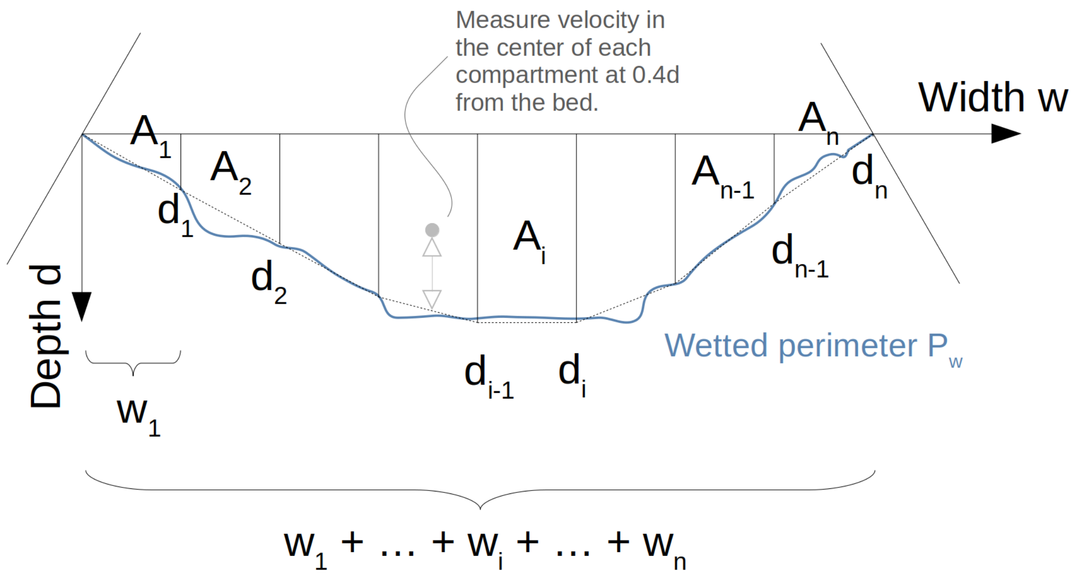


Figure 1: River cross-section and illustration of the compartments. An estimate of the wetted perimeter P_w is given by the sum of twice the maximum depth and the channel width.

Current-meter

A current-meter consists of a small propeller mounted on a pole that is connected to a device which measures the frequency of the propeller rotation. This information can be converted into a stream velocity using the provided look-up tables, which were established during calibration experiments.
If we assume a purely laminar flow, the theory of fluid mechanics states that the stream velocity is expected to vary vertically following a parabolic function because of the zero velocity (no-slip condition) at the bottom of the stream bed. In case of a turbulent flow, we would get a logarithmic function. For this reason, velocity should ideally be measured at several depths for each interval along the river cross-section. Alternatively, a single measurement is best taken at 40% of the local depth (measured from the bed, see Fig. 1), which is typically the depth with the mean velocity. Errors in the measurements can be introduced by random occurrences of turbulent eddies during the establishment of the profile, by changes in water height or width of the stream. During the experiment you should also take care to estimate the uncertainty of your measurements.

Protocol

1. Select an appropriate cross-section: ideally there should be no plants, no big stones and the channel should be clearly defined.

2. Establish a point near the selected cross-section where the water level can be monitored during the measurements.

3. Inspect and measure the cross-section. Make a clear graphical sketch of the profile.

4. Plan the measurement points and protocol based on the sketch of the profile (see Fig. 1).

5. Perform the velocity measurements at the planned points. To do so, one should select a propeller adapted to the stream velocity. Report the water level immediately before and after each measurement, as well as any problems or noteworthy particularities encountered during the measurements.

6. Repeat measurements several times.

7. Develop a way to estimate measurement uncertainty.

8. Work out all the measurements to obtain total discharge Q.

Dipping bar or "Tauchstab nach Jens"

The principle of this method is the same as for the current-meter. The dipping bar (Tauchstab) can be used to measure the flow velocity based on the torque exerted on the bar by the streamflow. A metallic horizontal stick can be interlocked in the dipping bar to counterbalance the force of the flow. By varying the position of the horizontal stick, the torque it exerts on the bar is changed. At the position where the bar is kept vertically, it balances the torque that is created by the streamflow and the weight can be translated into a flow velocity using look-up tables. The dipping bar can be used in water down to a depth of 60 cm. It should be noted that contrary to the current-meter which measures velocity at a given depth, the force exerted on the bar by the stream results from the integral of the flow velocity along the part of the bar that is immersed in the water. When using the dipping bar, remember to develop an estimate of measurement uncertainty.

Further tasks and questions Compare the measurements of integral flow velocity with the estimates from the more localized measurements of the current-meter. Are the two methods differently sensitive to different sources of uncertainty? Discuss for which occasions the cross-sectional velocity measurement is suited best and where it might be outperformed by other methods.

f) Tracer method (instantaneous injection)

Tracers are often used in mountain streams with high turbulence and without clearly defined channel. A good tracer needs to be non-reactive, besides it should be as harmless as possible for the environment. During the field course, we will measure the discharge using sodium chloride or salt (NaCl) as a tracer, by applying the instantaneous injection method. After having defined an appropriate location to conduct the experiment, a known amount of tracer is poured into the river in one go. This should be done upstream of where the measurements are taken, at a distance sufficient enough from the first measurement location, so that the tracer can get well mixed before reaching it.
The concentration of the tracer is then monitored by measuring the electric conductance in the river. Ideally, the following conditions have to be fulfilled: (i) the background concentration of the stream has to be known, (ii) it should not change during the experiment, (iii) the tracer is totally intermixed with the water in the stream (no backwater effects), and (iv) there are no water losses nor inputs between the injection and measurement locations. Using several measurement sites and/or several measurement devices enables to check the results by repeating the experiment. The relationship between the electrical conductivity and the NaCl-concentration has to be calibrated before starting the experiment. Then, one can plot the concentration as a function of time. The resulting curve

will typically look like that in Fig. 2. Finally, the discharge can be calculated using a mass balance equation

$$Q = \frac{M}{\int_{t_s}^{t_e} c(t) - c_0 \; dt} \approx \frac{M}{\sum_{i=1}^{n} \Delta t_i (c_i - c_0)} \; , \tag{8}$$

where $c(t)$ is the measured concentration over time from measurement start (t_s) to end (t_e), c_0 the background concentration of the stream and M the injected mass of the tracer $M = V_I c_I$, the product of injected water volume and tracer concentration in that volume.

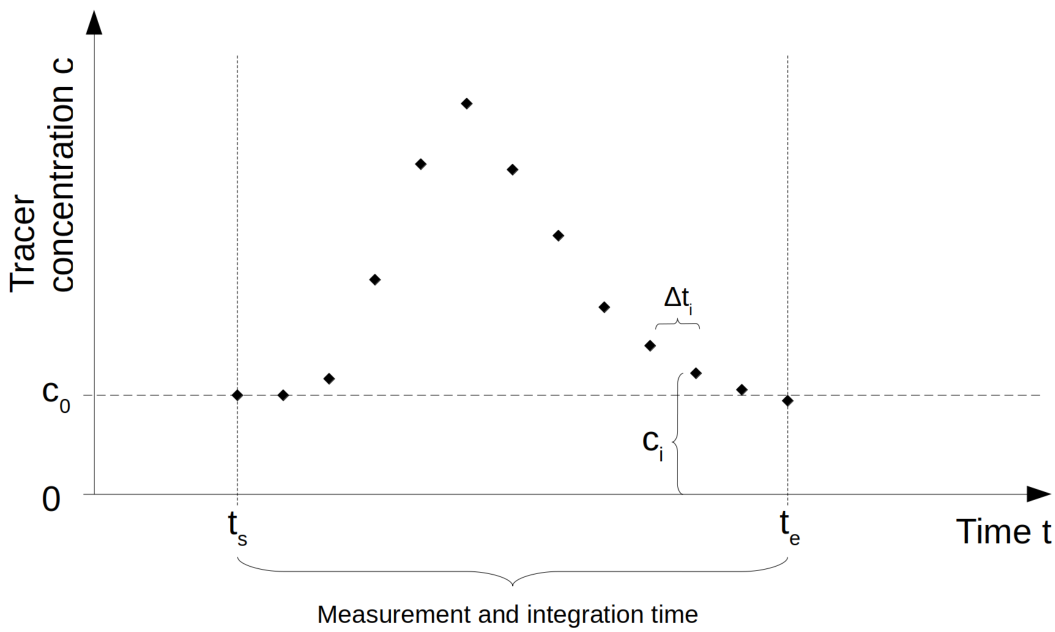


Figure 2: Typical evolution of the tracer concentration during a discharge measurement using the instantaneous injection method.

Protocol

1. Establish the relation between the electric conductivity and the NaCl-concentration. First, fill water of the river into a bucket and measure the conductivity. Then add precisely known amounts of salt to the bucket, stir well and measure the conductivity again. By adding more and more salt to the bucket and measuring the conductivity you can establish the calibration curve.

2. Select a location along the river with enough turbulence so that the tracer gets well mixed. Estimate the distance which is necessary to intermix the tracer using e.g. Hull [1958]: $L = 50\sqrt{Q}$ or Fischer [1966]: $L = 100W^2/d$, where Q is discharge, W is the channel width and d the watzer table depth.

3. Place the sensors for the electric conductivity at different locations downstream of the injection point.

4. Inject the previously dissolved tracer instantaneously into the stream.

5. Measure the concentration evolution during the whole tracer transit.

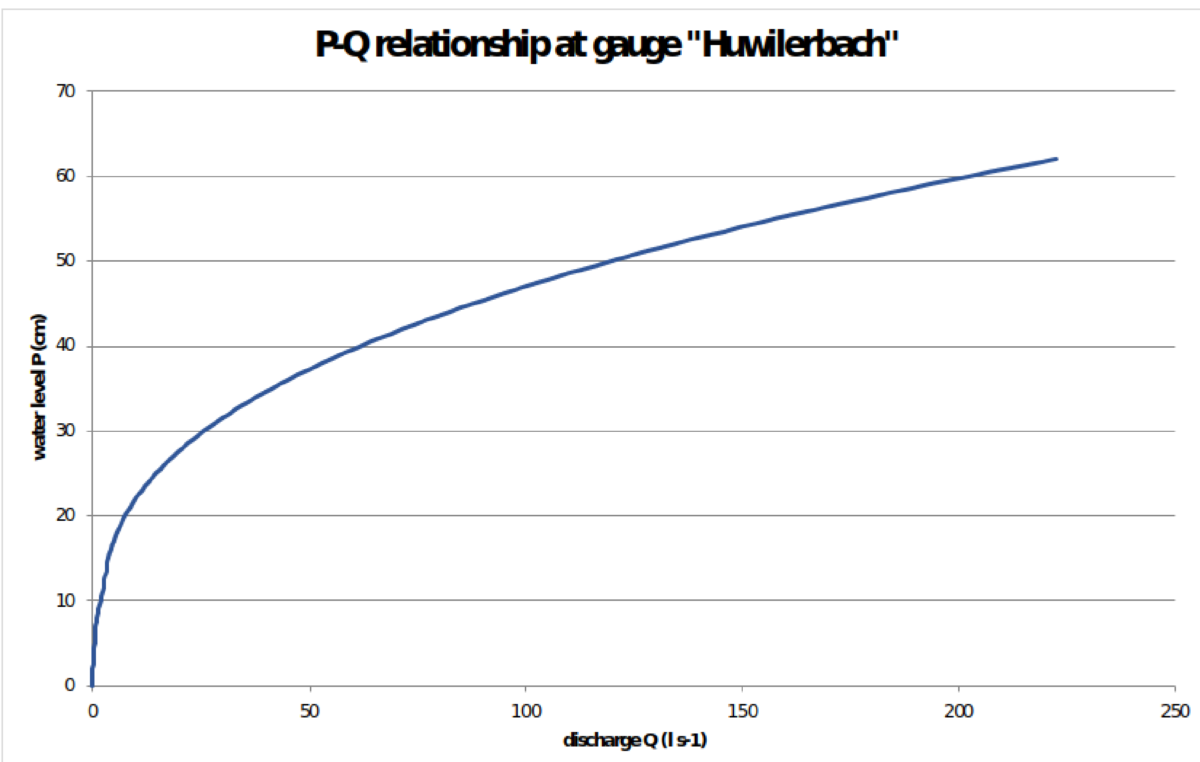
6. Calculate Q for the different devices and develop a notion of measurement uncertainty.

Further tasks and questions What are the main limitations of this method? Do all the assumptions at work apply to Rietholzbach?

3 Data analysis

Depending on the state of the streams, the discharge will be determined for the Rietholzbach and Huwilerbach rivers using several of the methods described above. Back in Zurich, the results will be reported, compared and discussed during the last two days of the field course week. For this analysis, you will obtain access to the automatic reference measurements from the Swiss Federal Office for the Environment for both Rietholzbach and Huwilerbach.
During the data analysis you will investigate different aspects of runoff measurements, e.g. year-to-year and seasonal variability of runoff, the influence of significant meteorological events on runoff and a thorough uncertainty estimation of your measurements. A synthesis of advantages and shortcomings of different techniques will allow a discussion of possible applications of the explored measurement techniques.

Appendix I: P-Q relationship Huwilerbach



W in cm	Q in l/s	W in cm	Q in l/s	W in cm	Q in l/s	W in cm	Q in l/s	W in cm	Q in l/s	W in cm	Q in l/s
0.0	0.00	10.0	1.63	20.0	7.44	30.0	25.71	40.0	61.93	50.0	119.82
0.5	0.00	10.5	1.84	20.5	7.99	30.5	27.06	40.5	64.28	50.5	123.34
1.0	0.01	11.0	2.07	21.0	8.58	31.0	28.45	41.0	66.68	51.0	126.93
1.5	0.01	11.5	2.31	21.5	9.20	31.5	29.90	41.5	69.15	51.5	130.58
2.0	0.03	12.0	2.57	22.0	9.86	32.0	31.39	42.0	71.66	52.0	134.29
2.5	0.05	12.5	2.69	22.5	10.56	32.5	32.92	42.5	74.24	52.5	138.06
3.0	0.08	13.0	2.83	23.0	11.29	33.0	34.51	43.0	76.87	53.0	141.90
3.5	0.12	13.5	2.98	23.5	12.06	33.5	36.14	43.5	79.55	53.5	145.80
4.0	0.17	14.0	3.17	24.0	12.86	34.0	37.82	44.0	82.30	54.0	149.77
4.5	0.22	14.5	3.37	24.5	13.71	34.5	39.55	44.5	85.10	54.5	153.81
5.0	0.29	15.0	3.60	25.0	14.59	35.0	41.32	45.0	87.96	55.0	157.90
5.5	0.37	15.5	3.85	25.5	15.52	35.5	43.15	45.5	90.87	55.5	162.07
6.0	0.46	16.0	4.14	26.0	16.48	36.0	45.03	46.0	93.85	56.0	166.30
6.5	0.56	16.5	4.44	26.5	17.49	36.5	46.96	46.5	96.88	56.5	170.60
7.0	0.67	17.0	4.78	27.0	18.53	37.0	48.94	47.0	99.98	57.0	174.96
7.5	0.79	17.5	5.15	27.5	19.62	37.5	50.97	47.5	103.13	57.5	179.39
8.0	0.93	18.0	5.54	28.0	20.75	38.0	53.06	48.0	106.35	58.0	183.89
8.5	1.09	18.5	5.97	28.5	21.92	38.5	55.19	48.5	109.63	58.5	188.45
9.0	1.25	19.0	6.42	29.0	23.14	39.0	57.38	49.0	112.96	59.0	193.09
9.5	1.44	19.5	6.91	29.5	24.40	39.5	59.63	49.5	116.36	59.5	197.79

Appendix II: Manning's n for river channels

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at floodstage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. same as above, but more stones and weeds	0.030	0.035	0.040
c. clean, winding, some pools and shoals	0.033	0.040	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.050
e. same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. same as "d" with more stones	0.045	0.050	0.060
g. sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. bottom: cobbles with large boulders	0.040	0.050	0.070

Figure 3: Manning's n for Channels [Chow, 1959]. Source: `www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm`

References

V. T. Chow. *Open channel hydraulics*. McGraw-Hill Book Co., Inc., New York, N.Y., 10-11, 1959.

Hugo B. Fischer. *LONGITUDINAL DISPERSION IN LABORATORY AND NATURAL STREAMS*. PhD thesis, 1966. URL `https://www.proquest.com/dissertations-theses/longitudinal-dispersion-laboratory-natural/docview/302207181/se-2`. Copyright - Database copyright ProQuest LLC; ProQuest does not claim copyright in the individual underlying works; Zuletzt aktualisiert - 2023-02-23.

D.E. Hull. The total-count technique: A new principle in flow measurement. *The International Journal of Applied Radiation and Isotopes*, 4(1):1–15, 1958. ISSN 0020-708X. doi: https://doi.org/10.1016/0020-708X(58)90020-6. URL `https://www.sciencedirect.com/science/article/pii/0020708X58900206`.