1 Runoff measurements

Streamflow is the part of the hydrologic cycle what can be measured most accurately, compared to precipitation, evaporation or evapotranspiration (Subramanya, 2008). Runoff is measured in volume per time (m^3/s).

Every method has a different accuracy and financial demand. The method has to comply with the financial resources and the accuracy request of the project. Also the study site has to be analysed to choose an accurate measuring technique, depending on the physical setting, flow velocity or water depth. It is important to know for example the flow conditions (stable or unstable), vegetation or obstacles in the river bed or profile geometry. Here, only the most common methods for measuring discharge of mountainous basins are presented.

Table 1 List of runoff measurement techniques for continuous automatic sampling or momentary sampling. *For water level measurements, momentary sampling is needed to derive the relationship between stage and discharge

Sampling frequency	Technique
Momentary sampling or Continuous manual sampling	Water level measurements* (staff gauge) Area-velocity measurements Tracer methods
Continuous automatic sampling	Water level measurements* (ultrasonic sensor, pressure probe)

The different methods are roughly separated into two groups (Table 4).

The first group refers to momentary sampling and continuous, but manual sampling. A continuous manual sampling would be chosen, for instance, to measure glacier discharge manually twice a day during one ablation period.

The second group of techniques can be applied for sampling runoff continuously and automatically. Continuous runoff data are typically deduced from stage measurements. For these relatively inexpensive techniques, careful manual runoff measurements at different stage levels are required to relate discharge to the elvation of the water surface (stage). Discharge in then estimated using the previously determined stage-discharge relationship.

These methods however, are inaccurate if the riverbed changes its profile over time. After a flood event for example, the stage–discharge relation has to be resampled manually. To overcome this limitation, a possible solution is to fixate the profile of the sampling site (see Figure 57). To ensure trouble-free operation, a station should be checked and calibrated frequently.

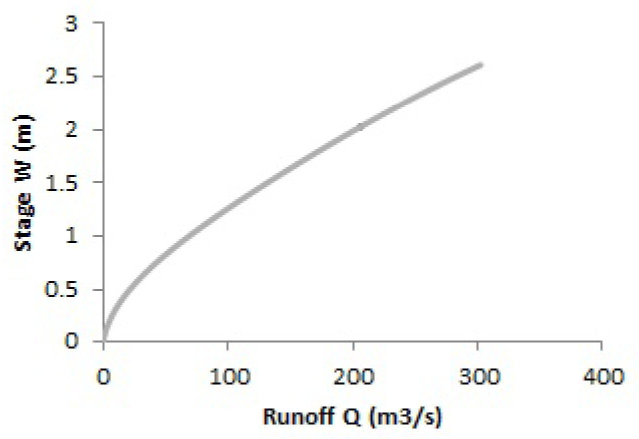


Figure 1 Example of a stage-discharge relationship

The stage-discharge relationship (Figure 45) is assumed to follow a potential curve which is expressed as

$$Q = a(W - b)^n \quad (1)$$

Q	discharge
W	water surface level
a, n	parameters of the potential function
b	Elevation difference between the elevation where stage is zero and river bed elevation

Common methods to measure stage level of a river are staff gauges, Ultrasonic water level sensor or pressure probes, as explained in the following Chapters.

1.1 Water level measurements

1.1.1 Staff gauge

The staff gauge is the simplest technique to measure the water level of a water body (Figure 46). The elevation of the water surface is noted using a graduated staff. The staff is fixed to a structure (e.g. bridge, large stone or wall) and made of a durable material with a low coefficient of expansion. The graduation of the staff allows reading water surface elevation with an accuracy of around 1 cm.

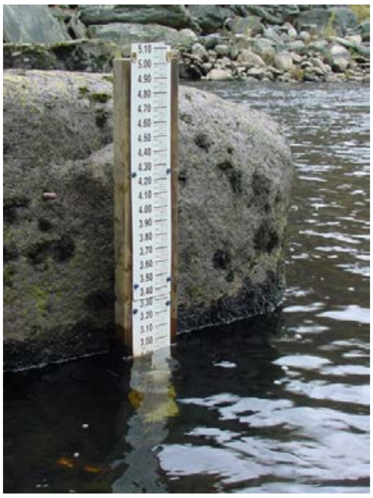


Figure 2 Example of a record site with a staff gauge (Crawford, 2012)

1.1.2 Ultrasonic water level sensor

A common method to record stage is the ultrasonic range sensor (Figure 47). It is important to mount the sensor perpendicular to the water surface. The water level is determined by sending out ultrasonic sound wave. The sensor records the time it takes for sound waves to reach the water surface and to return to the sensor face after rebounding on the water surface. An internal temperature sensor automatically compensates for the temperature related variation in the speed of sound and a 15-second averaging time reduces the effects of turbulence in the water. Ultrasonic sensors are usually very precise and have a good resolution. An advantage is also that they are usually not very expensive compared to other water level sensors (600$ to 800$).

Figure 3 Students installing an ultrasonic water level sensor below a bridge (Picture taken by S. Schauwecker) to measure discharge of a glacierized catchment in the Chilean Andes and a picture of a Sommer UPM-8 Ultrasonic Water Level Sensor (Fondriest Environmental, 2012)

1.1.3 Pressure probe

The pressure probe is another sensor which is often used in water level measurements in relatively large rivers or lakes (Figure 48). This sensor measures pressure which is dependent on the water level. The changes in pressure of the atmosphere are automatically corrected. The sensor is mounted above the river with the sensor end at the bottom of the flume or at least below the minimum expected water level. A cable containing the sensor signals is connected to a data logger mounted above the flood stage.

Advantages of the pressure probe are that they are very durable and easy to use. The disadvantage is that the sensor has to be installed in the river and therefore it is very vulnerable to flood events. A minimum depth is needed to install this device. An approximate cost of a pressure probe is $900. Figure 48 illustrates an example of a pressure probe which is protected by a PVC tube.

Figure 4 A pressure probe in a tube, mounted at the same sampling site as the ultrasonic water level sensor in Figure 47 and an example of a pressure probe (www.nexsens.com)

1.1.4 Water-stage recorder

The measurement principle of water-stage recorders is to record the rise and fall of a water surface with respect to time. Water from the river enters a vertical tube through an underwater pipe and allows that the water surface inside the vertical tube is at the same elevation as the water surface of the river. This principle is called “stilling well”.

One common method is using a float and a counter weight, which are moved vertically if water surface level changes. This movement is recorded via a deflection pulley to a paper roll. As this method is very robust and easy to operate, these devices are in use since more than 100 years and still widespread to record water level.

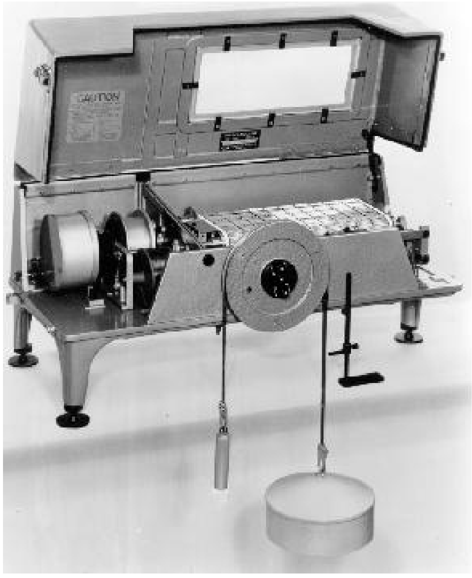


Figure 5 Continuous recording water-stage recorder with cover raised. The time element rotates the rolls, and the height element records parallel to the axis of the rolls (www.usbr.gov)

1.2 Area-velocity method

The most common methods to measure runoff are velocity measurements. In addition to the runoff determination, the area of the river cross section has to be known or otherwise, it has to be sampled (Figure 50). A great obstacle in the operation of current meters is the irregular pulsation of turbulent flow, which is often the case in the discharge of a glacier.

1.2.1 Current meter

One of the most important and accurate methods is the current meter (Figure 51), which is a reliable instrument for flow investigation and discharge measurements in natural and artificial channels. The advantages of the method are its relatively high precision and the fact that it can be used to sample large river beds. A current meter, in use since 1790, has a rotating element, namely screw or wheel. If water flows along the instrument, the wheel is rotated and from the speed of the rotating element, runoff velocity can be derived, assuming that the number of rotations is proportional to the flow velocity. An error occurs if the stream direction is not parallel with the axis of rotation.

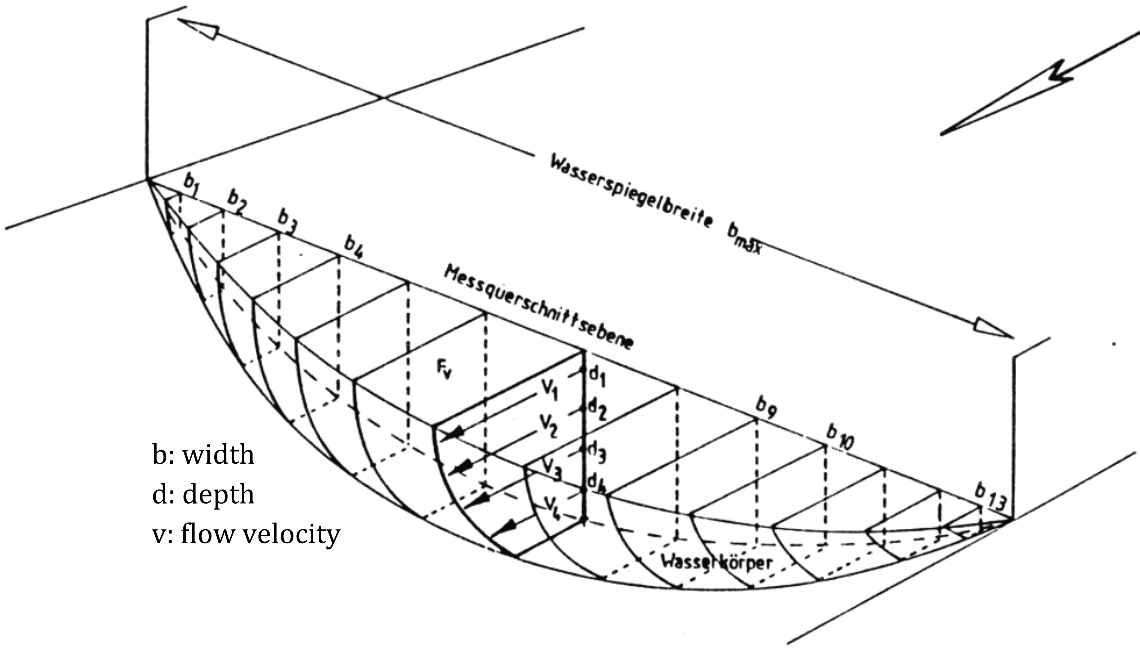
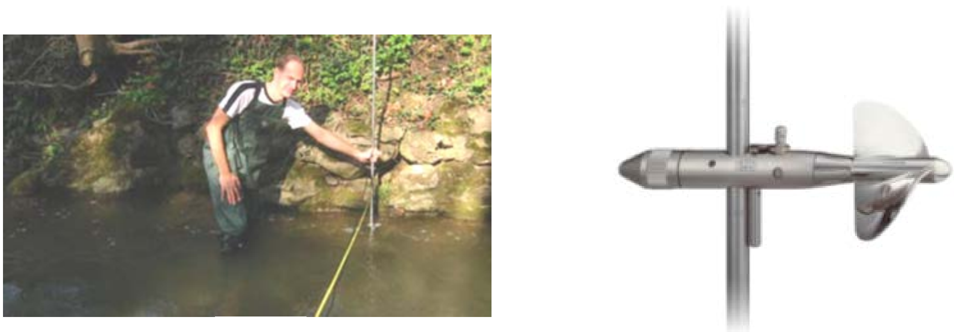


Figure 6 Technique of runoff measurement with a current meter (Landeshydrologie, 1982)



(a) (b)

Figure 7 (a) Student measuring flow velocity (Braun, 2009) (b) picture of a current meter

The flow velocity is measured by a cross section of the river at different points (Figure 50). Total discharge is then calculated as

$$Q = v \cdot A \; [m^3 s^{-1}] \qquad (2)$$

Where A is the profile area and v the mean velocity of the sampling profile which can be derived integrating the sampling points over the geometry of the cross section.

Constraints and requirement

There are some constraints which could limit the application of a current meter to measure discharge in the foreland of a glacier:

- the water depth should be at least 10 cm
- the direction of the flow lines should be perpendicular to the sample profile
- few turbulence; laminar flow conditions
- little vegetation or ice in the cross section

- the runoff must be constant during the measuring time
- stable discharge area

Besides the current meter, there is a variety of other current meters like acoustic or electromagnetic methods.

1.2.2. Velocity sensor

The measurement principle of a velocity sensor is based on the Doppler Effect. The sensor sends an ultrasonic signal to the flow stream. Those signals are reflected off bubbles and particles, and return to the sensor with a frequency shift (Doppler Effect) proportional to velocity. A differential pressure transducer in the sensor measures liquid depth. Flow rate is calculated by multiplying the wetted area of the flow stream by its average velocity. When installing an area velocity sensor in the stream, be sure to position it in an area that best represents the average velocity. (www.isco.com)

1.2.3. Tracer methods

Generally, tracer methods consist of the following steps: first, a known amount of a tracer substance is added to the river and in a second step the concentration of the tracer is measured at a certain distance river down to calculate discharge Q. The idea of this method is that a small measured concentration indicates a large discharge and on the other hand a large measured concentration indicates a small discharge.

Dilution methods are used for rivers where it is difficult to gage with current meters due to shallow water, uneven rocky bottom, and irregular wavy surface or turbulent fluxes. This is why it is a common method to sample glacier in the foreland of glaciers.

Table 5 shows a comparison between constant-rate and momentary injection of salt (NaCl). These two methods are described in the following two chapters. The use of salt as a tracer has several advantages. The concentration can be measured easily by a conductivity meter and salt can be bought in every food shop. It is not polluting the water, chemically stable and dissolvable in water.

Table 2 Comparison between constant-rate and momentary injection of salt (Braun, 2009).

	Constant-rate injection	**Momentary injection**
Salt concentration	Stationary conditions (integration over time is not needed)	Non stationary condition (integration over time is needed)
Important dimension	Injected salt concentration (g/s)	Injected salt amount (g)
Calculation method	Load balance for salt (g/s)	Mass balance for salt (g)
Discharge Q	Assumption: Q is constant over measuring period	Assumption: Q is constant over measuring period

Tracer methods with salt as a tracer substance are based on the relation between conductivity and salt concentration (Figure 52). Every water body has a so called ground conductivity which is explained by dissolved minerals. It is important to measure the ground conductivity before injecting the salt dilution. For the tracer method with salt, the relationship between salt concentration and conductivity is linear. Hence, it is possible to deduce salt concentration from conductivity and ground conductivity measurements. The calibration line in Figure 52 is derived in the field or in the laboratory by a stepwise increase of salt concentration. The calibration curve is derived by a linear regression:

$$c = a(L - L_0) \tag{3}$$

c	salt concentration (g/l)
a	slope gradient of regression line (g µS^{-1} l^{-1})
L	conductivity (µS)
L_0	ground conductivity (µS)

To estimate the minimal distance between injection and sampling site, a simple rule is proposed:

$$L = \frac{100B^2v}{4D} \tag{4}$$

With

$$D = 2.5\sqrt{vQ} \tag{5}$$

B	mean width of river channel (m)
D	dispersion coefficient (m²/s)
v	estimated mean flow velocity (m/s)
Q	estimated discharge (m³/s)

Note that this is only a very rough estimation. Generally has to be considered that the larger the ratio between channel width and depth, the larger the mixing distance.

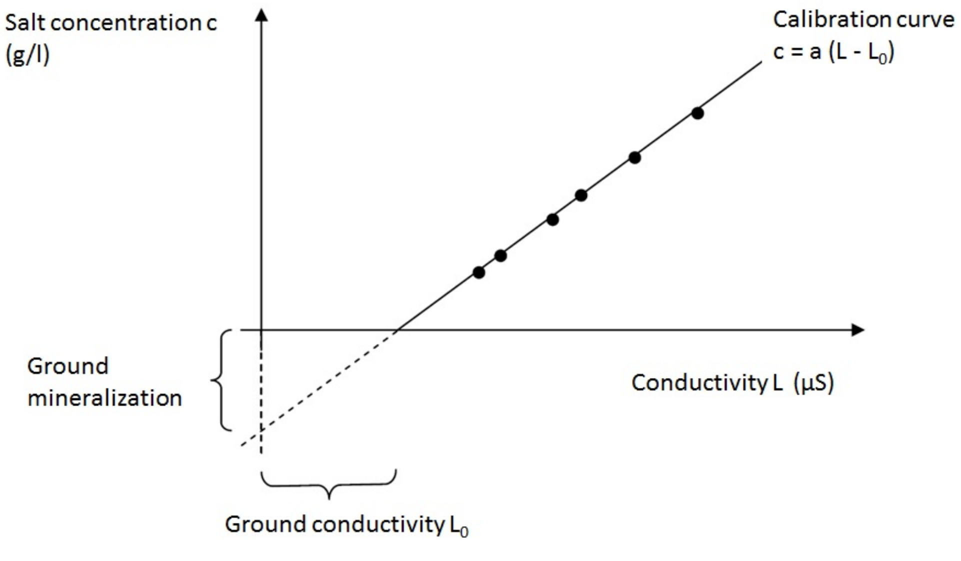


Figure 8 Salt concentration in function of conductivity

1.2.4. Constant-rate injection method

The constant-rate-injection method involves adding a tracer solution of a determined concentration and volumetric flow to a stream. It is injected continuously for a certain time so that an equilibrium concentration is established at a sampling station downstream. It is very important that the dilution is completely mixed at the sampling site. The time of injection has to be chosen in a way that the tracer concentration at the sampling point is constant.

For the injection of the salt dilution, a Mariotte's bottle can be used (Figure 53). It is a device that delivers a constant rate of flow from a closed bottle or tank. The outflow rate is regulated by the pressure at the bottom of the air inlet. The pressure remains constant as long as the water level lies below the air inlet and this allows delivering a flow under constant head height, regardless of the water level within the bottle.

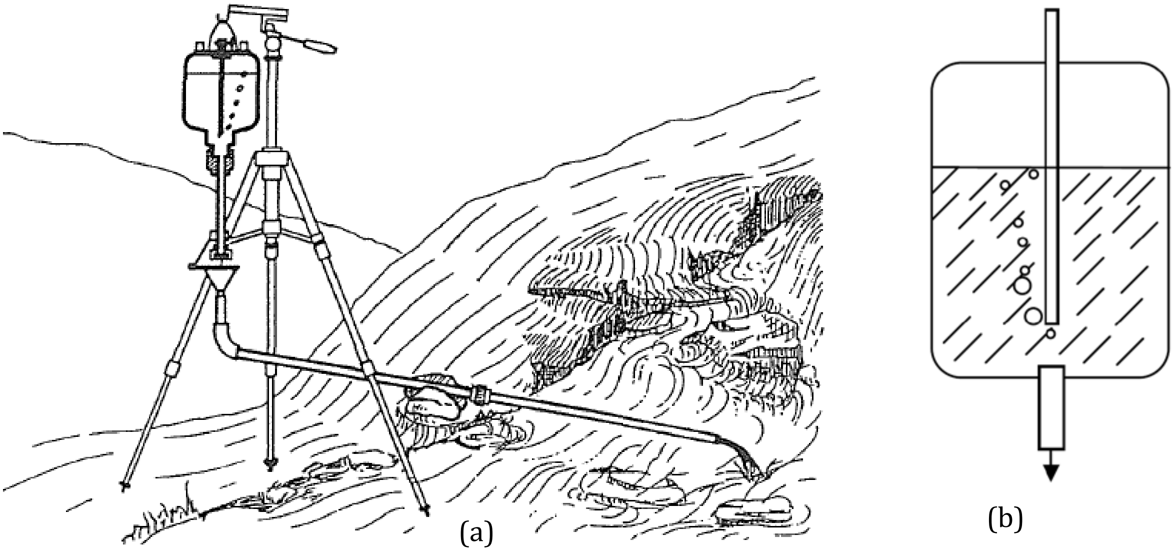


Figure 9 (a) Installation of a Marriotte's bottle and (b)schematic of a Marriotte's bottle

F_0, Q

Assuming a stationary flow condition, discharge Q is calculated based on the load balance for salt. The load of salt flowing out of Marriotte's bottle F_M (g/s) plus the background load of the river F_0 are equal to the load of salt in the river F_2, where the salt concentration is measured.

F_M, Q_M

$$F_M + F_0 = F_2 \tag{6}$$

thus

$$Q_M c_1 + Q c_0 = (Q + Q_M) c_2 \tag{7}$$

and consequently

$$Q = \frac{Q_t(c_1 - c_2)}{(c_2 - c_0)} \tag{8}$$

F_1	salt load at injection site
F_2	salt load measured at sampling site
Q_t	discharge from Marriotte's bottle
Q	discharge at sampling site
c_1	salt concentration in Marriotte's bottle
c_2	measured concentration at sampling site
c_0	background concentration

Constraints and requirement

The following conditions must be fulfilled (Gees, 1990).

- the amount of tracer injection must be constant during the measurement
- the method requires that the same amount of tracer per time passes the sampling cross section as was injected (no exfiltration or infiltration)
- the tracers must be stable
- turbulent flow between the injection and the sampling point
- The tracer must be completely mixed with the river water and at the sampling cross section distributed homogenously
- the background level of the river water must be stable

1.2.5. Integration (gulp) method

This method is also called integration or gulp method as a simple gulp of tracer solution is added to the river (Figure 54). At the sampling station the passage of the entire tracer cloud is monitored to determine the relationship between the concentration and time. The important parameter is the amount of salt injected to the river. The salt is dissolved in a bucket with water and then injected momentary to the water body. A simple rule of thumb helps to estimate the amount of salt that has to be injected to the studied river:

$$M_{bucket}(g) = 2\ to\ 6\ times\ Q_{estimated}\ (ls^{-1}) \quad (9)$$

Figure 10 The dissolved salt is injected momentary by a student (Braun, 2009)

The discharge is calculated of the mass balance equation for the injected salt (the mass of salt in the bucket has to be equal to the mass of salt measured at sampling site):

$$M_{bucket} = c_1 V_{bucket} = Q \int_{t_1}^{t_2} (c_2 - c_0)\, dt \quad (10)$$

The discrete form of this equation to calculate discharge:

$$Q = \frac{M_{bucket}}{\sum_{i=1}^{n} c_i \Delta t_i} = \frac{M_{bucket}}{\sum_{i=1}^{n}\big(a(L_i - L_0)\big)\Delta t_i} \quad (11)$$

M_{bucket} quantity of tracer dissolved in the bucket
c_1 concentration
v_{bucket} volume of the initial tracer solution

t_1 time before the leading edge of the tracer cloud arrives at the sampling point
t_2 time after all the tracer has passed this point
c_0 background tracer concentration
c_2 recorded tracer concentration
L_i measured conductivity
L_0 ground conductivity

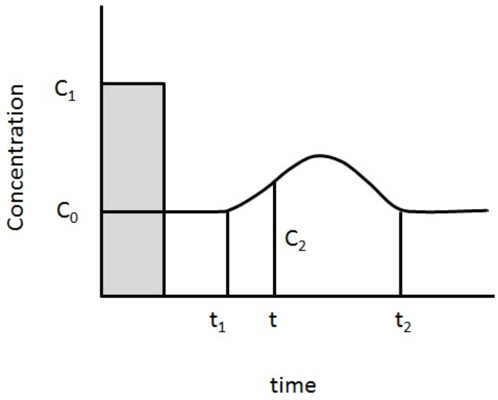


Figure 11 Schematic of sudden-injection method. The grey area illustrates the sudden injection of a volume V_{bucket} of dissolved salt with concentration c_1 (Subramanya, 2008).

When the entire tracer cloud has passed the sampling point, runoff can be calculated from the concentration-time diagram (Figure 55).

Constraints and requirement

The following conditions must be fulfilled (Gees, 1990):

- the exact amount of tracer must be known
- the tracer added to the river must be completely diluted
- the runoff should be constant
- all the tracer must pass the sampling cross section
- flow must be turbulent between the injection and the sampling point
- no dead water between the injection and sampling point
- in order to get a good mixture of the tracer over the whole cross section it must be diluted homogenously
- the tracer must be stable
- the background level (conductivity) of the river should be stable

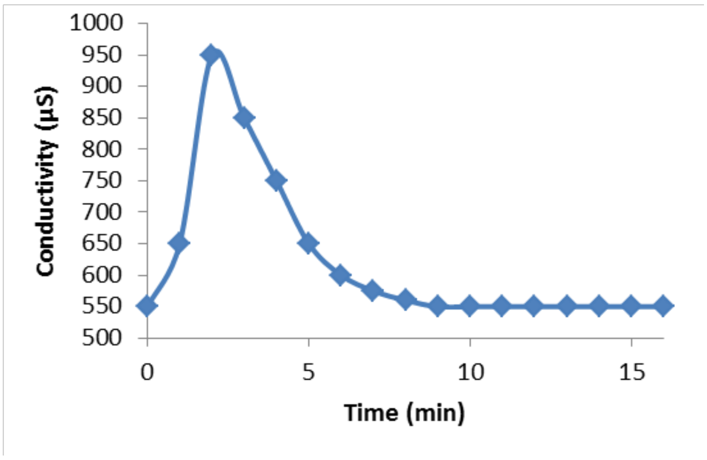


Figure 12 Measurement of conductivity at sampling site after injection of a "gulp" of salt dilution. The time was set to zero when the dilution was arrived at the sampling site.

1.3. Examples

Wooden staff calibrated with current meter

Hasnain (1999) measured daily mean discharge of Dokriani Bamak, a small Himalayan glacier in Uttarkashi district of Uttar Pradesh. They measured discharge with a wooden staff. For the stage-discharge relationship they measured cross section using dip-sticks and flow velocity with a current meter. (Hasnain, 1999)

Radar water level measurements calibrated with salt dilution

Ragettli and Pellicciotti (2012) used discharge measurements on Juncal Norte catchment, Chile, which were obtained through a combination of salt dilution experiments and radar water level measurements. The dilution experiments provide a very accurate record of discrete measurements which were used to reconstruct a rating curve from which the continuous, 5-minute water level readings of a VEGA radar device were converted into runoff. (Ragettli & Pellicciotti, 2012)

Fixated runoff gage with ultrasonic sensor and pressure probe

Jonas (2019) monitored hydrological processes in mountainous catchments. The profile of the monitored Albertibach was fixated at the runoff gage (see Figure 57), because a changing riverbed leads to inaccuracy of continuous runoff measurements. The stage is picked up by an ultrasonic range sensor as well as by a pressure probe in the measuring channel. (Jonas, 2010)

Water level recorders calibrated with area-velocity method and manual observation of staff gauge

Thayyen and Gergan (2009) measured discharge of a glacierized catchment at three sampling points over 6 ablation periods. The discharge was calculated from a rating curve established by the area-velocity *(not specified)* method. For continuous recordings of water level at these three stations, water level recorders *(not specified)* were installed over the stilling wells made of steel drums. Manual observations of staff gauges were also carried out four times a day, with three hour intervals to overcome the problems arising from malfunction of the chart recorder during high flow periods of June to August. The chart recording was disturbed many times during the study period due to high flows and other mechanical problems. One station was washed off during a high flow in July 2001. (Thayyen & Gergan J T, 2009)

Gauging station

Figure 13 Channel in a mountainous river at the gauging station (Escher-Vetter, 2011)

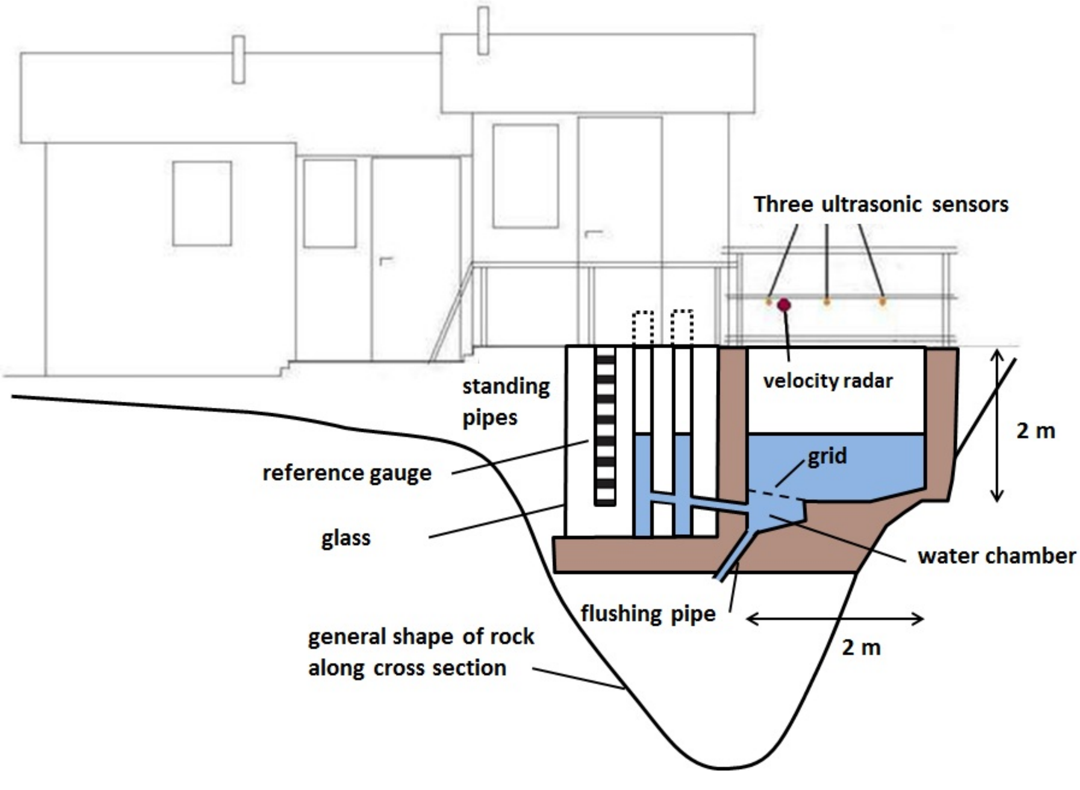


Figure 14 Cross section of measurement principle at Vernagtbach gauging station. (Bergmann & Reinwarth, 1976)

The Vernagtbach gauging station is a representative example for a permanent sample site. The gauging station was built in 1973 and is recording since 1973. It is located in the Oetz Valley Alps and measures glacier discharge at an elevation of 2635 m. The Vernagtbach drainage basin covers an area of 11.44 km^2 and is approximately 72% glacierized.

Figure 58 depicts the cross section with the measurement setup at the gauging station. Runoff is measured in a channel of 2 m width and 2 m height with a trapezium profile. The length of the measuring channel is 4.2 m not including the inflow area. The flushing pipe is used to evacuate continuously the accumulation of sediment (primarily sand) in the water chamber.

The measurement method is a combination of continuous recording of stage level and occasional measurements of discharge.

Table 3 List of runoff measurement techniques for continuous automatic sampling or momentary sampling used at the Vernagtbach gauging station.

Sampling frequency	**Technique**
Momentary sampling or Continuous manual sampling	Flow velocity sensor Integration (gulp) method with salt as a tracer
Continuous automatic sampling	Water level measurements: two communicating pipes and three ultrasonic sensors

They use two methods to measure water level. The first method is via two standing pipes (working as "stilling wells" which operate as a system of communicating pipes. The water level is recorded with a float, connected through a wire to a stage recorder. A reference staff gauge is installed to check manually the water stage of the two standing pipes.

The second method is using three ultrasonic sensors, placed along the profile at different positions. They are fixed to a bridge above the cross section and directed vertically to the water surface.

The gulp injection method is conduced around 50 times during the year for several discharges, in order to derive the stage-discharge relation.

The standing pipes are installed behind a glass wall. The glass acts as Greenhouse and thus heating through solar radiation prevents early freezing of the water surface in the standing pipes. (Hanisch, 2011)

2. Acronyms

DDF	Degree Day Factor
DEM	Digital Elevation Model
IPCC	Intergovernmental Panel on Climate Change
GCM	General circulation model
CMIP5	Coupled Model Intercomparison Project
WGCM	Working Group on Coubled Modelling
WCRP	World Climate Research Programme
SRES	Special Report on Emissions Scenarios
RCP	Representative Concentration Pathways
RCM	Regional climate model
SRM	Snowmelt runoff Model
NMI	Normalized melt index