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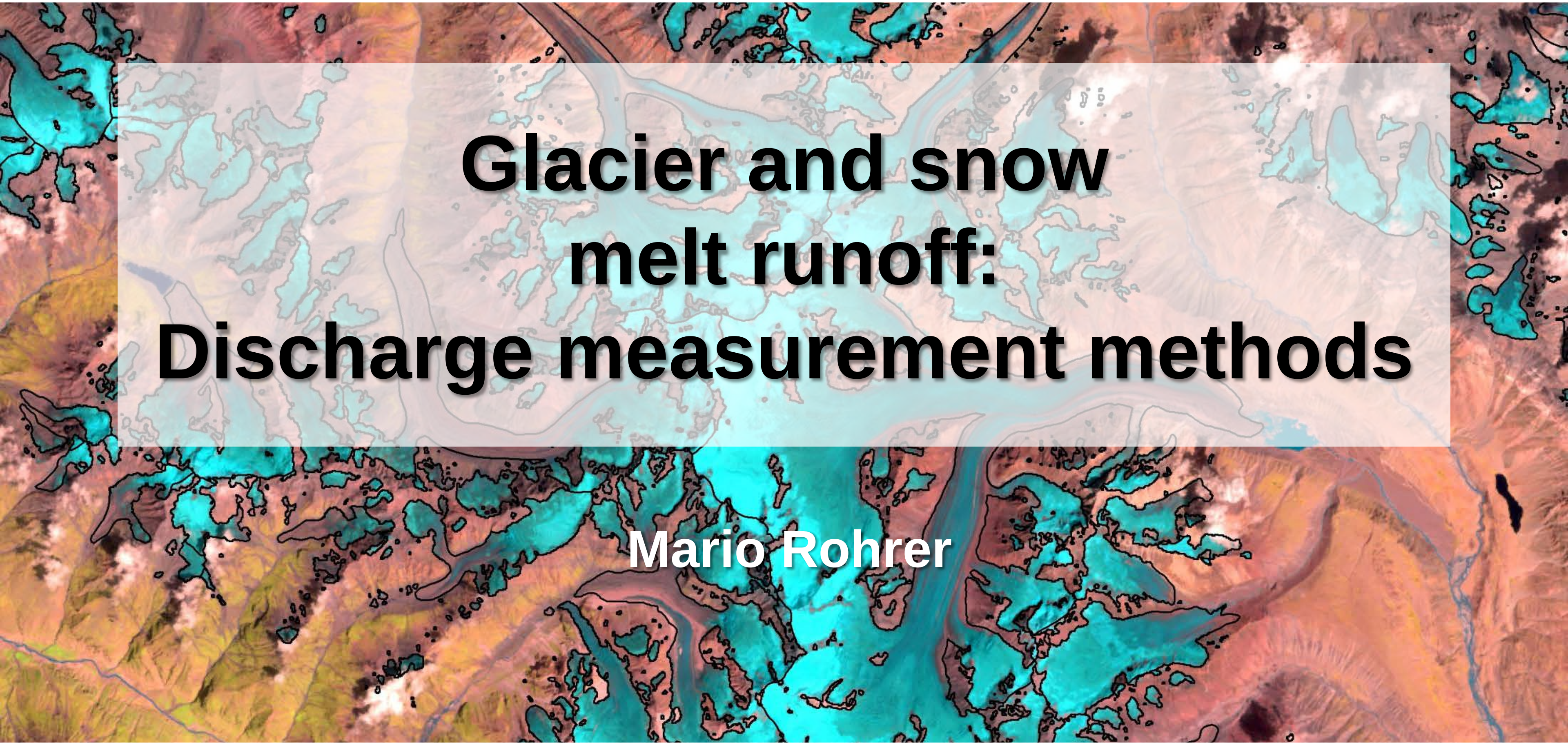

Glacier and snow melt runoff: Discharge measurement methods

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IHCAP – Indian Himalayas Climate Change Adaptation Programme
Capacity building programme “Cryosphere” Level-2 (January, 2015)

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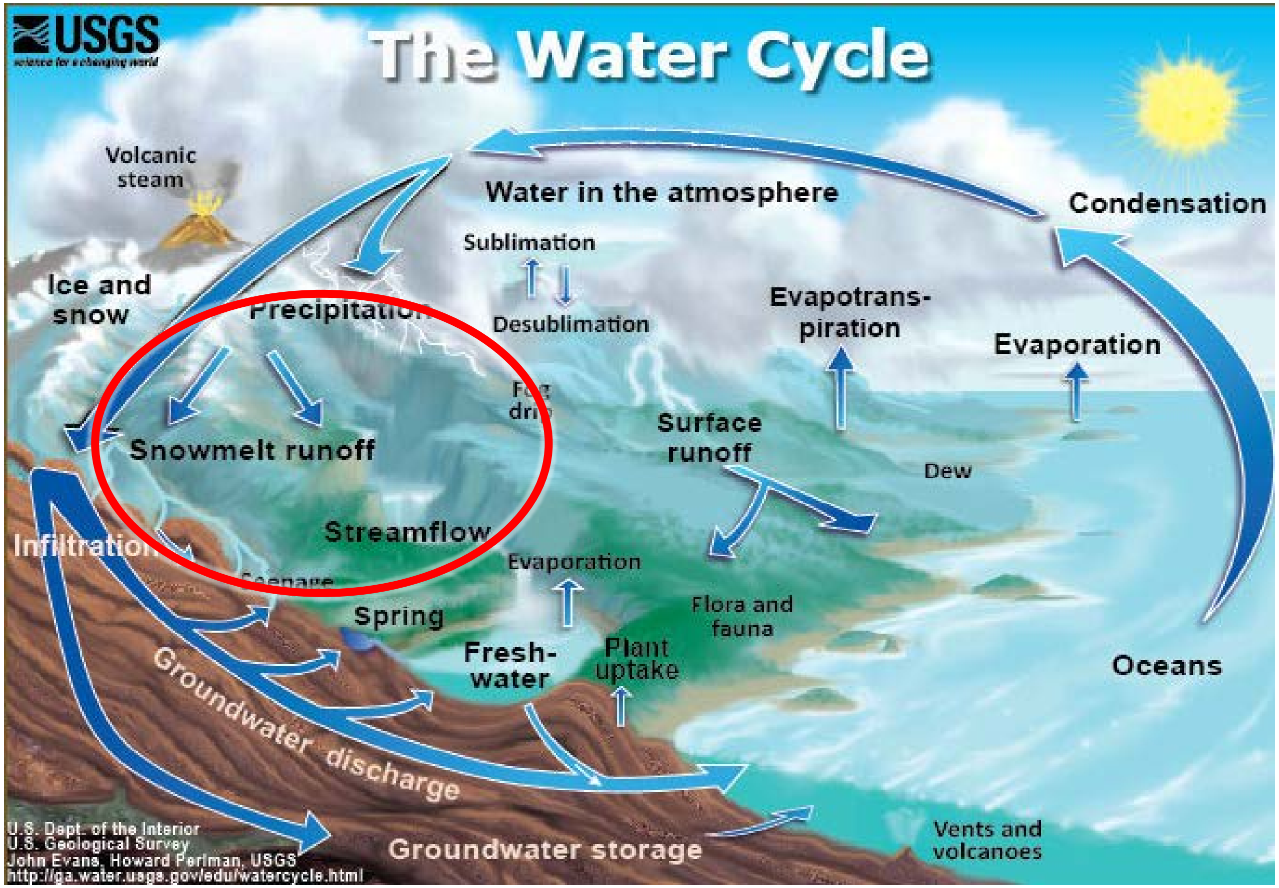
1. Introduction

Streamflow



Streamflow is the element of the hydrologic cycle that can be measured in the most accurate way, compared to precipitation, evaporation or evapotranspiration

1. Introduction

Most common methods

The measuring technique is chosen depending on:

- needed accuracy
- financial resources

And depending on the physical setting:

- flow velocity
- water depth
- flow conditions
- obstacles in the river bed
- profile geometry
- other

Figure Bridge crossing glacier discharge, looking upstream at discharge gauging site (photo: T. Stott, http://www.ljmu.ac.uk/NSP/121517.htm)

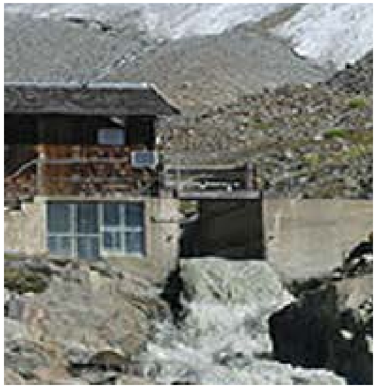
1. Introduction

Most common methods

Sampling frequency	Technique
Manual sampling (momentary or continuous)	• Water level measurements* (staff gauge) • Area-velocity measurements • Tracer methods
Automatic sampling (continuous)	• Water level measurements* (ultrasonic sensor, pressure probe)

*For water level measurements, momentary sampling is needed to derive the relationship between stage and discharge

http://b506m.wordpress.com/2012/12/



1. Introduction

Stage - discharge relationship

For water level measurements, momentary sampling is needed to derive the relationship between stage and discharge

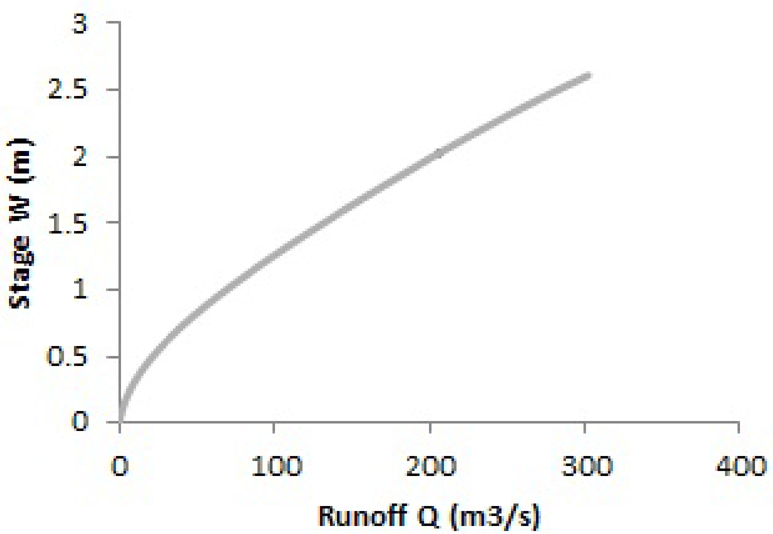


Figure Example of a stage-discharge relationship

Often stage-discharge relation can be approximated with the following fomula:

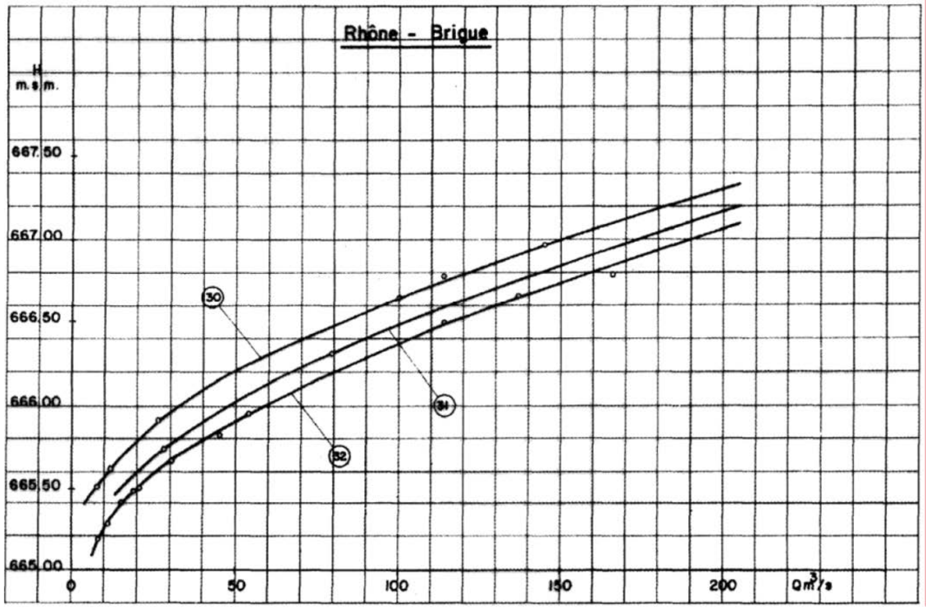
$$Q = a(W - b)^n$$

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

1. Introduction

Stage - discharge relationship

For water level measurements, momentary sampling is needed to derive the relationship between stage and discharge
Moreover, this rating curve has to be recalculated when river bed changes.



Example of 3 different stage-discharge relationships for the same measurement point (figure: BAFU)

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2. Water level measurements

Staff gauge

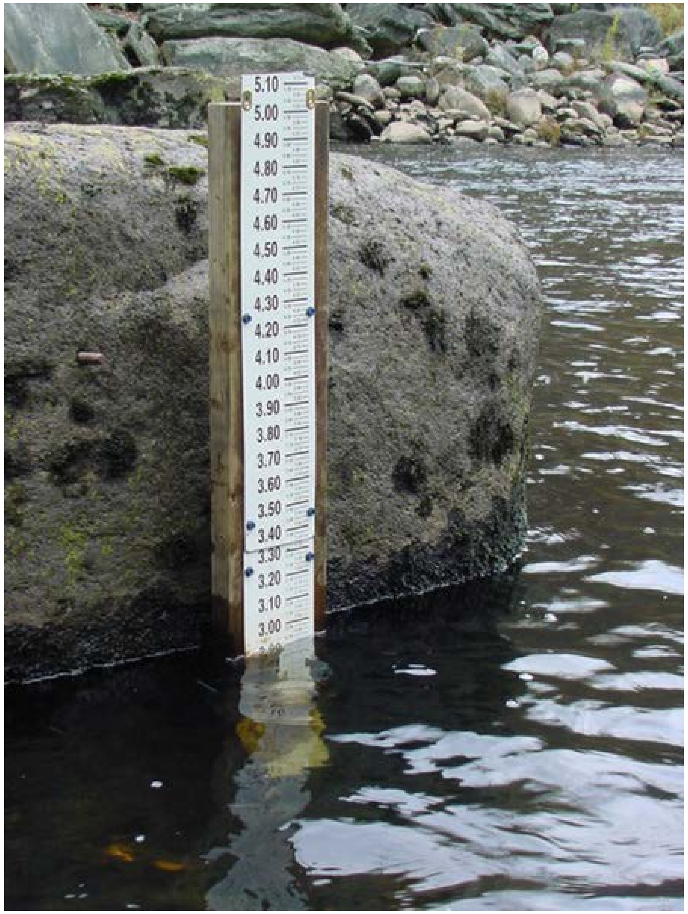


Figure Example of a record site with a staff gauge (Crawford, 2012)

- simplest technique
- elevation of water is noted using a graduated staff
- staff is fixed to a structure
- accuracy: around 1 cm

2. Water level measurements

Ultrasonic water level sensor

Figure Sommer UPM-8 Ultrasonic Water Level Sensor (Fondriest Environmental, 2012)

Figure Ultrasonic water level sensor below a bridge

- common method
- mount the sensor perpendicular to water surface
- ultrasonic sound waves
- very precise, good resolution
- not very expensive (~500 to 1000 USD)

2. Water level measurements

Pressure probe

Figure A pressure probe in a tube

Figure example of a pressure probe (www.nexsens.com)

- often used
- the sensor measures pressure which is dependent on the water level
- cable connected to data logger
- durable, easy to use
- vulnerable to flood events
- minimum depth is needed to install the device
- cost: approximately 1000 USD

2. Water level measurements

Water-stage recorder

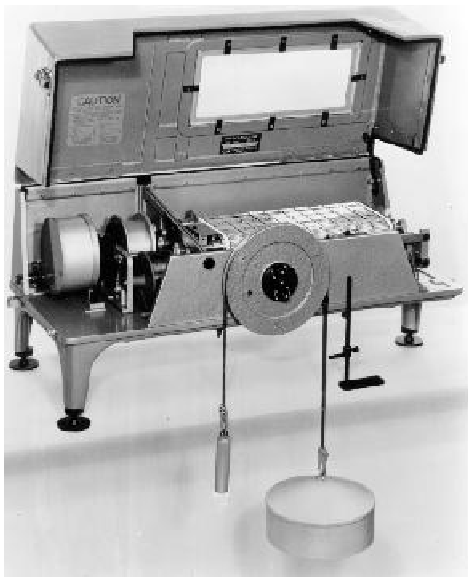


Figure Continuous recording water-stage recorder with cover raised. (www.usbr.gov)

- record the rise and fall of a water surface with respect to time
- water from river enters a vertical tube through an underwater pipe
- water in tube is at the same elevation as water surface of the river ("stilling well")
- float and counter weight moving vertically with changes in surface level
- movement is recorded via a deflection pullay to a paper roll

- robust method, easy to operate
- since more than 100 years

Contents

2. Area-velocity method

Current meter

Figure Current meter

- reliable instrument
- relatively high precision
- can be used to sample large river beds
- rotating element (screw or wheel)
- runoff velocity derived from rotation speed
- error if stream direction is not parallel

2. Area-velocity method

Current meter

The flow velocity is measured by a cross section of the river at different points.
Total discharge Q is then calculated as : $Q = v \cdot A\ [m^3 s^{-1}]$

A profile area
v the mean velocity of the sampling profile

v is derived integrating the sampling points over the geometry of the cross section.

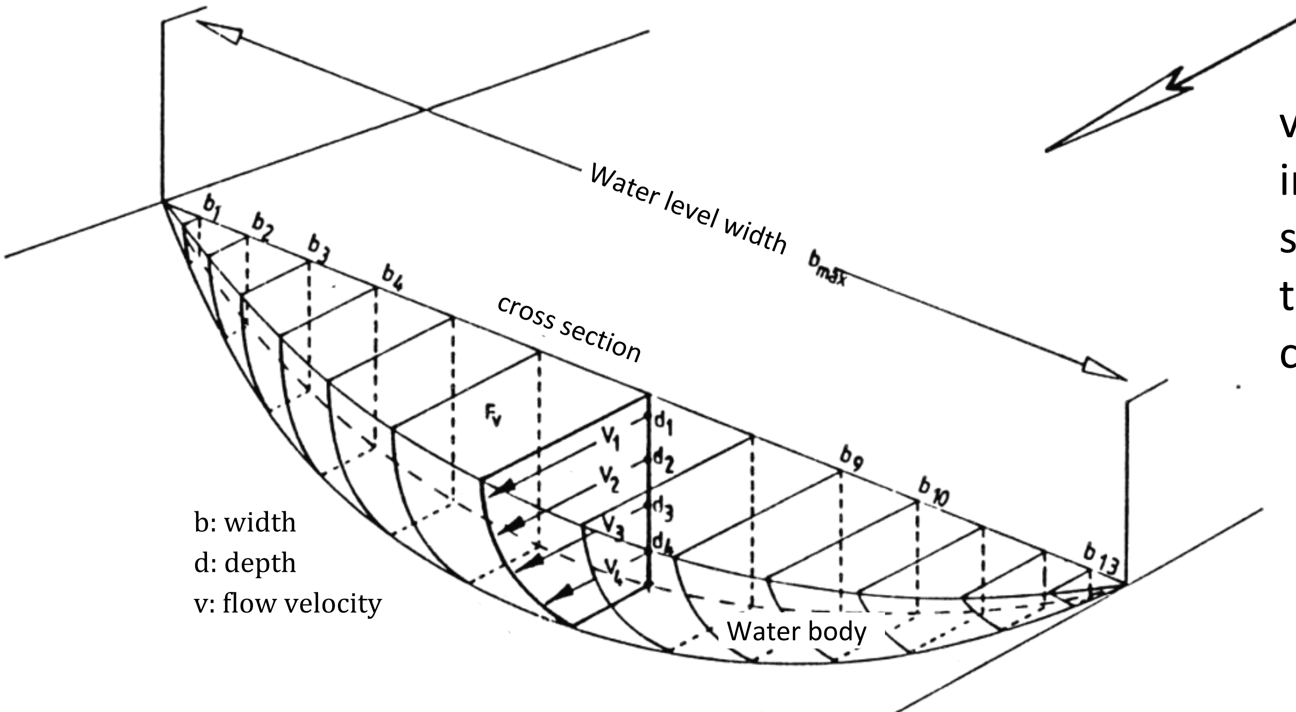


Figure Technique of runoff measurement with a current meter (Landeshydrologie, 1982)

2. Area-velocity method

Current meter: Constraints

- 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

2. Area-velocity method

Velocity sensor

Figure FlowTracker deployment in Central Queensland (Corbett, 2005)

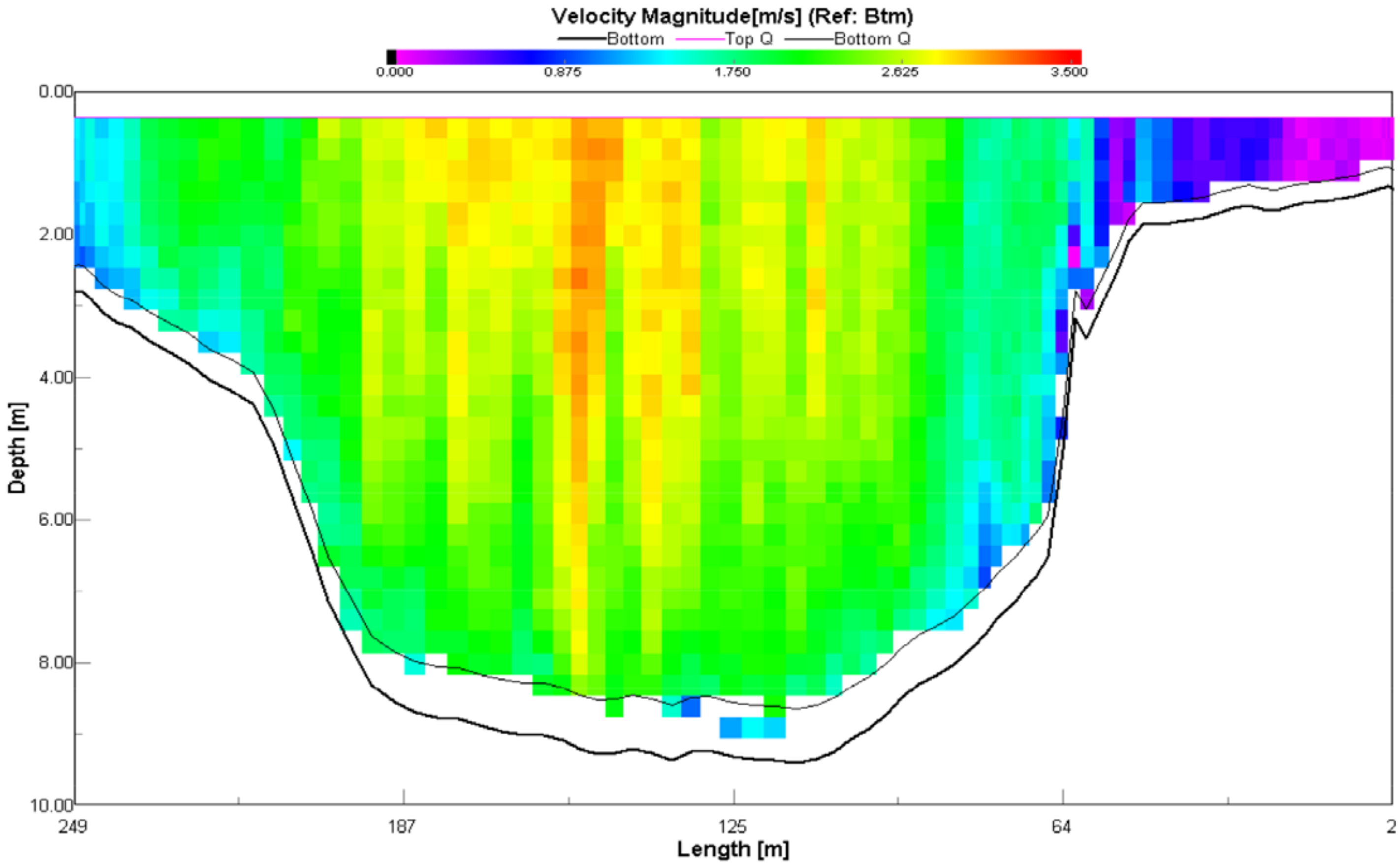
- based on Doppler Effect
- sensor sends an ultrasonic signal to the flow stream
- singals are reflected off bubbles and particles and return to the sensor with a frequency shift proportional to velocity

2. Area-velocity method: ADCP

Velocity sensor

- ADCP: Acoustic Doppler Current Profiler
- based on Doppler Effect
- sensor sends an ultrasonic signal to the flow stream
- Signals are reflected from bubbles and particles and return to the sensor with a frequency shift proportional to velocity

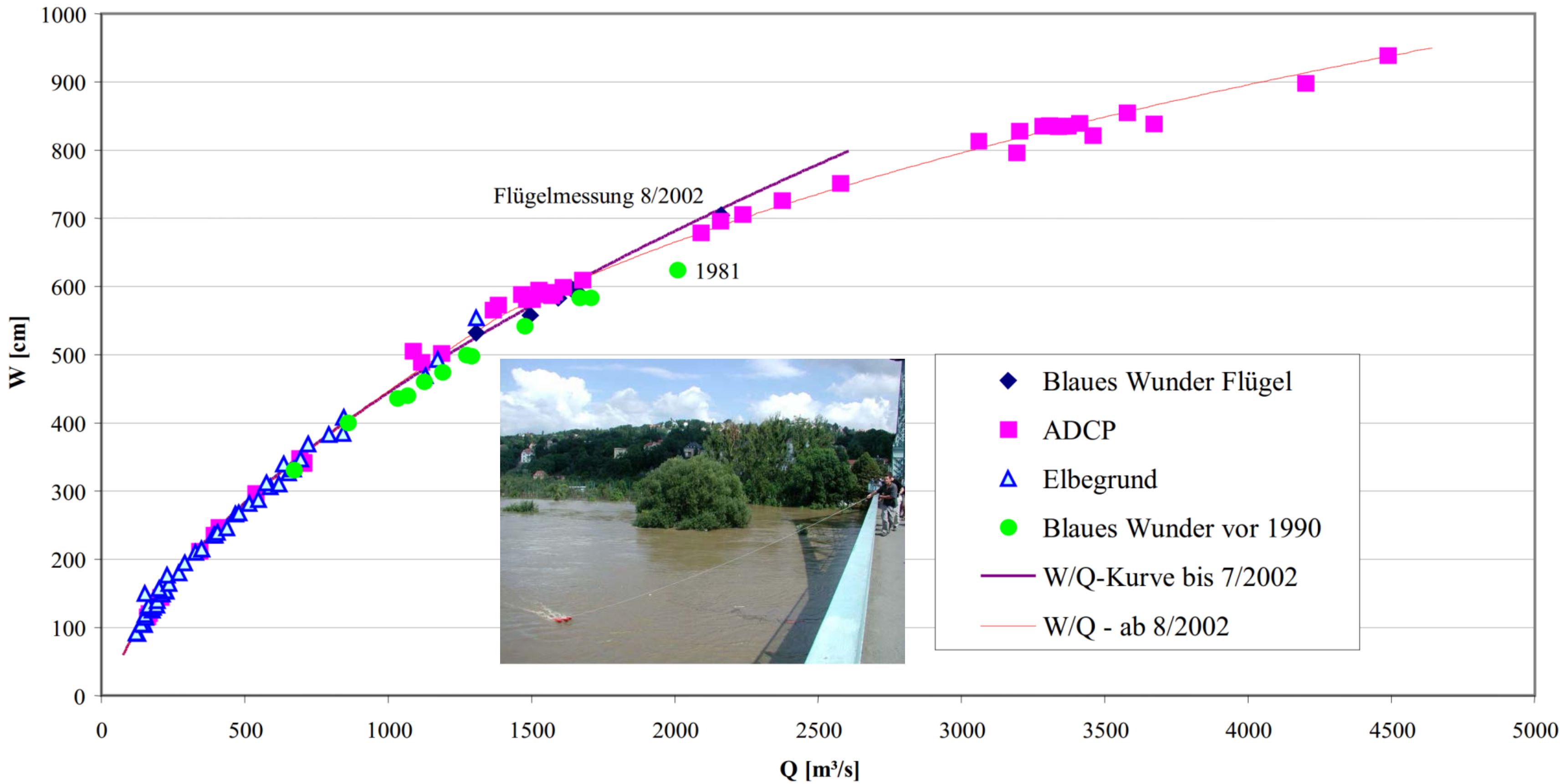
2. Area-velocity method: ADCP



Velocity profile of the Elbe river at Dresden from ADCP, fig: BA f. Gewässerkunde

2. Area-velocity method: ADCP

ADCP measurements under flood conditions



ADCP measurements at Elbe river in flood conditions (pink squares)

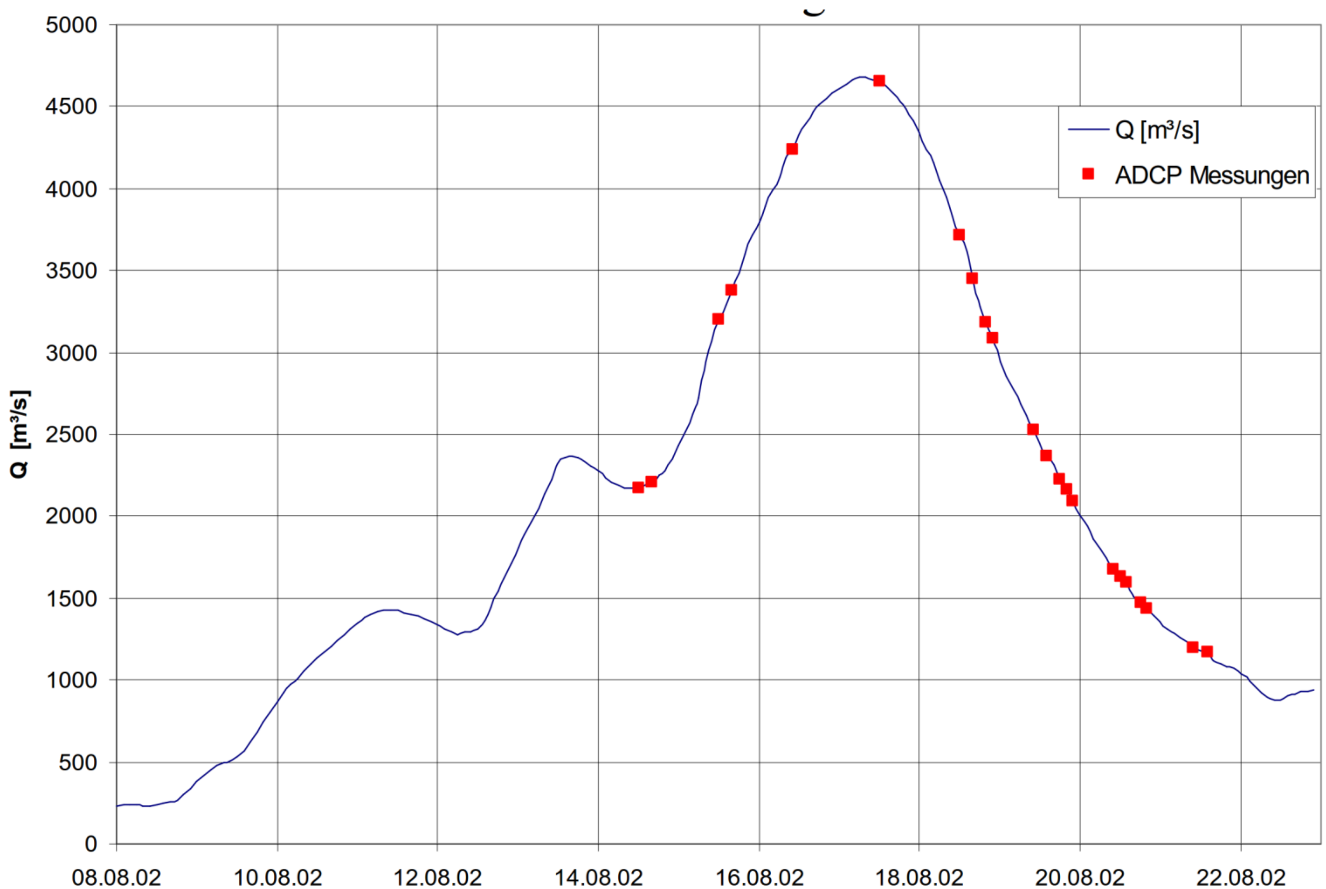
2. Area-velocity method: ADCP

Velocity measurement in flood conditions with ADCP efficient and fast, in contrast to hydrometric vane

Figure: BAFG

2. Area-velocity method: ADCP

Runoff estimation with ADCP during ELBE flood in Aug. 2002



Figure

Contents

3. Tracer methods

General information

1. a known amount of a tracer substance is added to the river
2. concentration of the tracer is measured at a certain distance river down to estimate discharge Q.

Figure: Sommer Messtechnik

3. Tracer methods

General information

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

Figure: Sommer Messtechnik

3. Tracer methods

General information

no information regarding the cross-section of the water needed

Suited for:

- Rivers where complete mixing of the tracer takes place
- fast-flowing, turbulent waters with complex cross-sections

Figure: Sommer Messtechnik

3. Tracer methods

General information

Salt and fluorescent sensors

Conductivity sensors

As tracer is common salt or road salt (NaCl) used which can be simply and uncomplicatedly entered into the waters.

The used conductivity sensors have an internal temperature compensation and are linearized according to EN27888 for natural water.

Tracer type	Conductivity sensor
Application	Discharges up to10 m³/s
Typical tracer insertion	approx. 5 kg per m³/s
Positive	• Easy to use • Cost-saving • Ease procurement of tracer

Fluorescence sensors

The advantage of using fluorescence sensors is the low minimum concentration for detection. Therefore, only very few tracer is added to the water and measurements of large discharge amounts are possible.

By default, the measurement units for fluorescence measurements are equipped with Uranine sensors. Optionally are used other optical sensors like Rhodamine sensors.

Tracer type	optical Fluorescence sensor
Application	All discharges
Typical tracer insertion	approx. 0.5 g per m³/s
Positive	• Low tracer amount • Low due to stress • High detection limit

Figure: Sommer Messtechnik

3. Tracer methods

Advantage of salt (NaCl)

- the concentration can be measured easily by a conductivity meter
- can be bought everywhere
- chemically stable and
- dissolvable in water

Figure Salt NaCl (wikipedia.com)

3. Tracer methods

Constant-rate vs. momentary injection

	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	

3. Tracer methods

Constant-rate vs. momentary injection

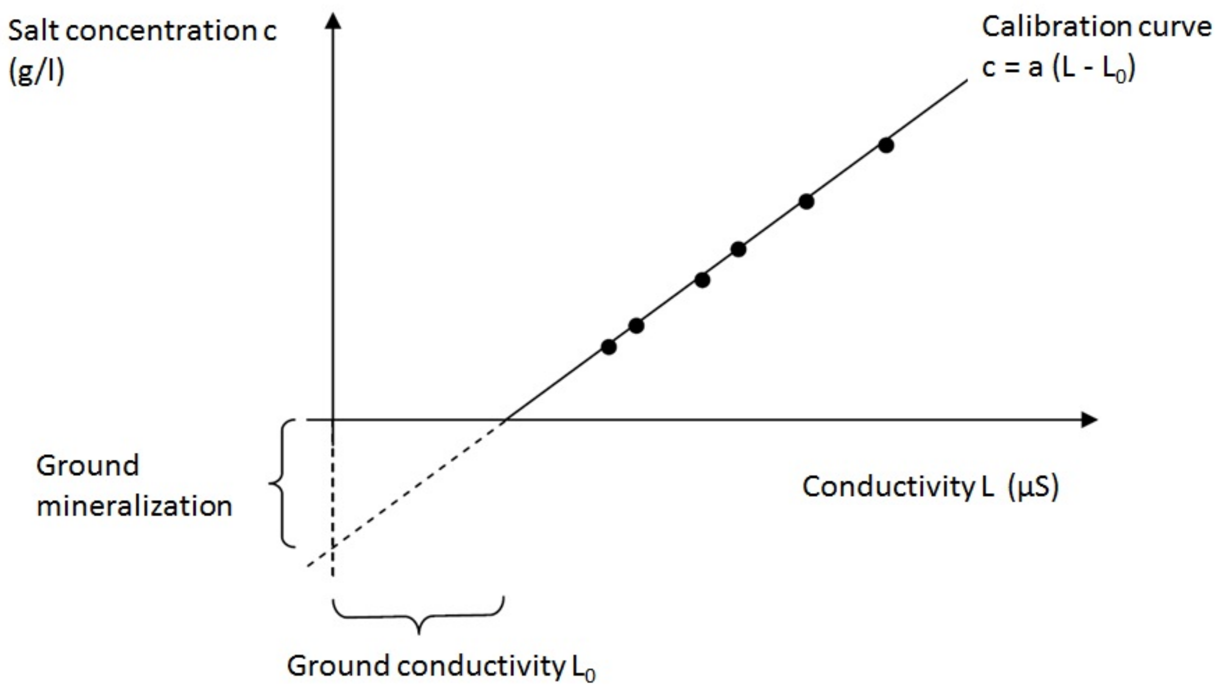
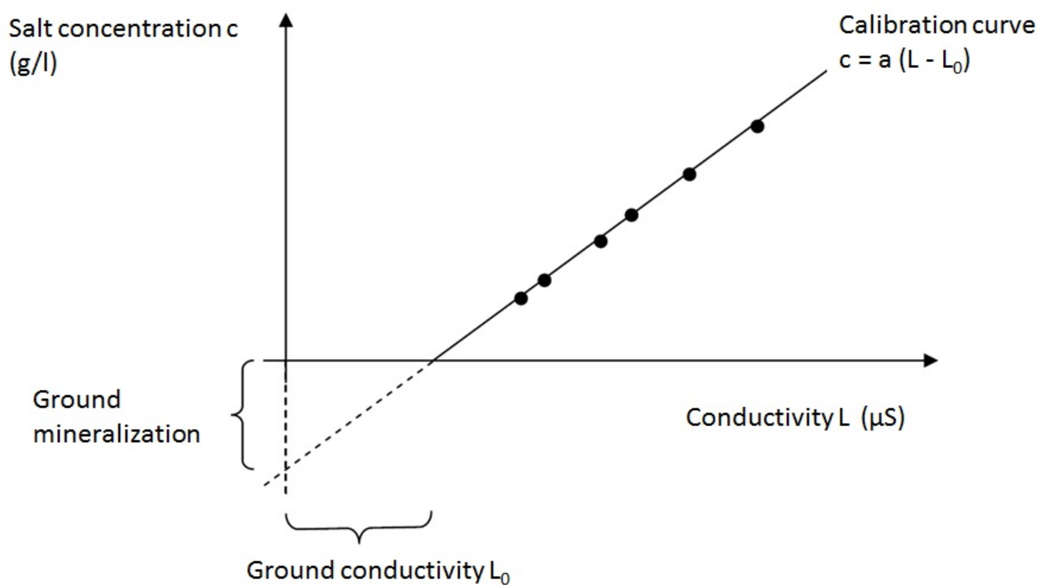


Figure Salt concentration in function of conductivity

- tracer methods with salt as a tracer are based on the relation between conductivity and salt concentration
- every water body has a ground conductivity
- therefore, it is important to measrue the ground conductivity before injecting the salt dilution
- the calibration curve is derived by a linear regression

3. Tracer methods

Constant-rate vs. momentary injection



$$c = a(L - L_0)$$

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

3. Tracer methods

Constant-rate vs. momentary injection

$$L = \frac{100B^2 v}{4D} \qquad \text{with} \qquad D = 2.5\sqrt{vQ}$$

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

With

B mean width of river channel (m)

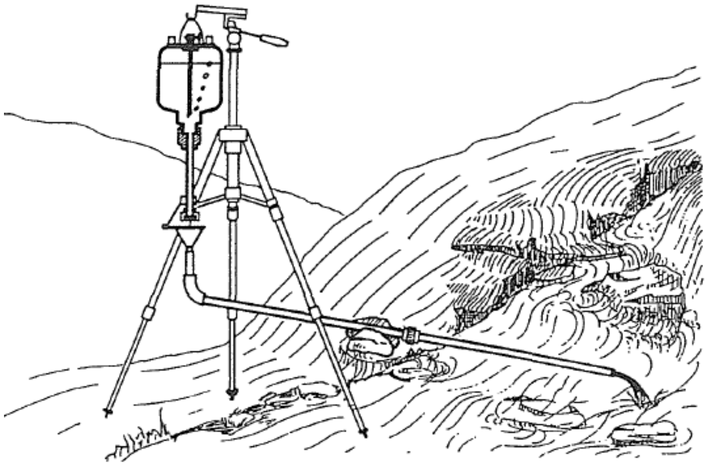
D dispersion coefficient (m^2/s)

v estimated mean flow velocity (m/s)

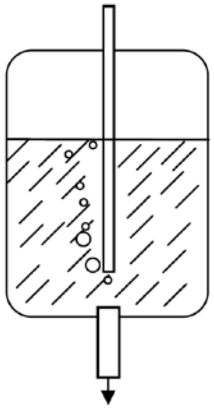
Q estimated discharge (m^3/s)

3. Tracer methods

Constant-rate injection method



- adding a tracer solution of a determined concentration and flow to a stream
- injected continuously for a certain time ro reach an equilibrium concentration at the sampling station downstream
- dilution needs to be mixed



- Mariotte's bottle for injection
- delivers constant flow rate

3. Tracer methods

Constant-rate injection method

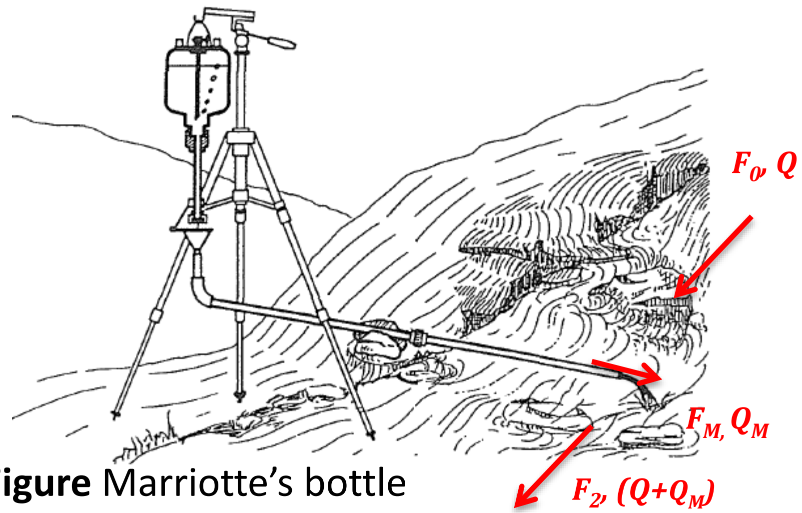


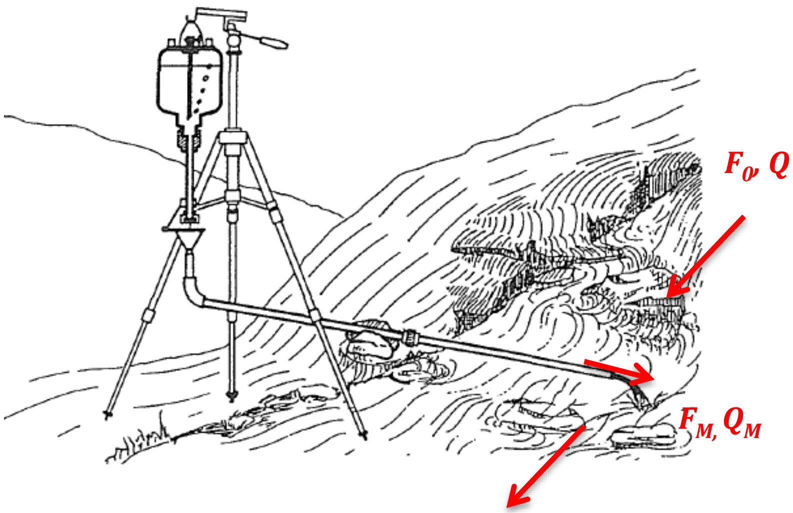
Figure Marriotte's bottle

- Assumption: 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)
+
the background load of the river F_0
=
to the load of salt in the river F_2, where the salt concentration is measured.

3. Tracer methods

Constant-rate injection method



$$F_M + F_0 = F_2$$

$$\Rightarrow Q_M\, c_1 + Q c_0 = (Q + Q_M) c_2$$

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

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

3. Tracer methods

Constant-rate injection method: requirements

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

3. Tracer methods

Constant-rate injection method: Exercise

A 25 g/l solution of a tracer was discharged into a stream at a constant rate of 10 cm^3/s. The background concentration of the tracer in the stream water was found to be zero. At a downstream section sufficiently far away, the salt was found to reach an equilibrium concentration of 5 parts per billion.

1. *Estimate the stream discharge (example from Subramanya, 2008).*
2. *What happens to the computed discharge if infiltration along the riverbed is high and 10% of the diluted salt gets lost?*
3. *List other possible sources of error.*

3. Tracer methods

Integration (gulp) method

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

3. Tracer methods

Integration (gulp) method

- integration or gulp method
- The salt is dissolved in a bucket with water and then injected momentary to the water body ("gulp").
- 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.
- A simple rule of thumb helps to estimate the amount of salt that has to be injected to the studied river:

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

3. Tracer methods

Integration (gulp) method

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):

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

The discrete form of this equation to calculate discharge:

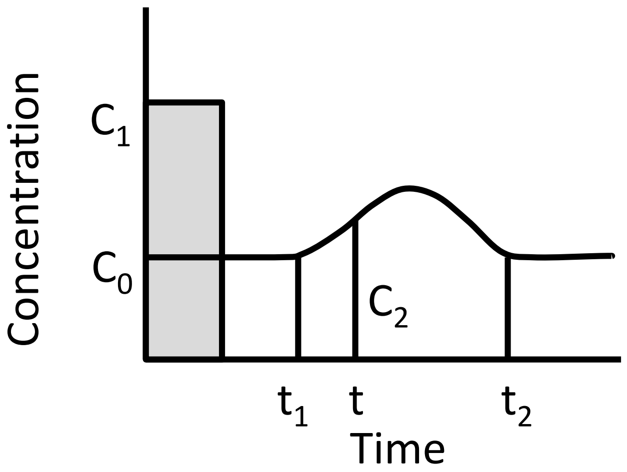
$$Q = \frac{M_{bucket}}{\sum_{i=1}^{n} c_i \Delta t_i} = \frac{M_{bucket}}{\sum_{i=1}^{n} \big(a(L_i - L_0)\big) \Delta t_i}$$

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

3. Tracer methods

Integration (gulp) method

When the entire tracer cloud has passed the sampling point, runoff can be calculated from the concentration-time diagram



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).

3. Tracer methods

Integration (gulp) method

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

3. Tracer methods

Integration (gulp) method

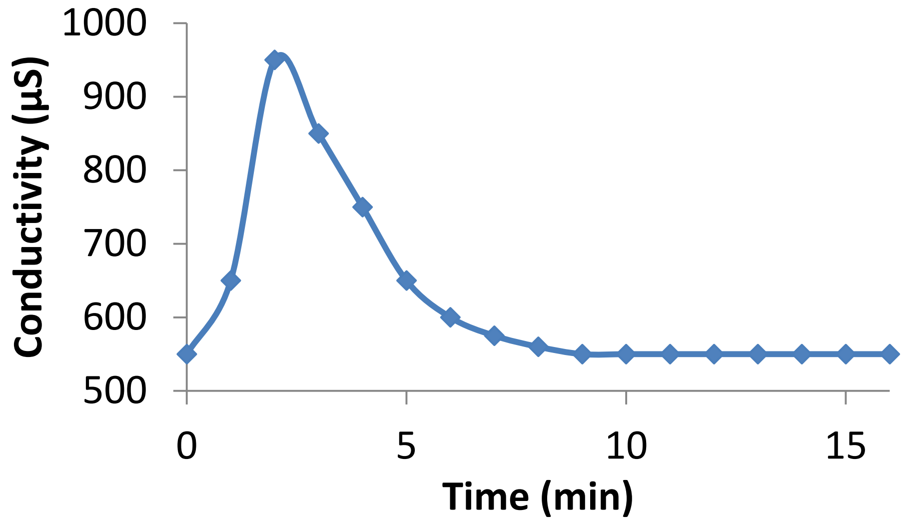


Figure Measurement of conductivity at sampling site after injection of a "gulp" of salt dilution. The time was set to zero when the dilution was arrived at the sampling site.

3. Tracer methods

Integration (gulp) method: Exercise

Compute discharge Q at the sampling site, knowing that the ground conductivity L_0 is 550 µS and the slope gradient a is 0.0003. For salt dilution 1 kg of salt was used.

Table Measured conductivity at the sampling site after injection of a "gulp" of salt dilution.

Time	(min)	0	1	2	3	4	5	6	7	8	9	10	11	12	13
L_i	(µS)	550	650	950	850	750	650	600	575	560	550	550	550	550	550

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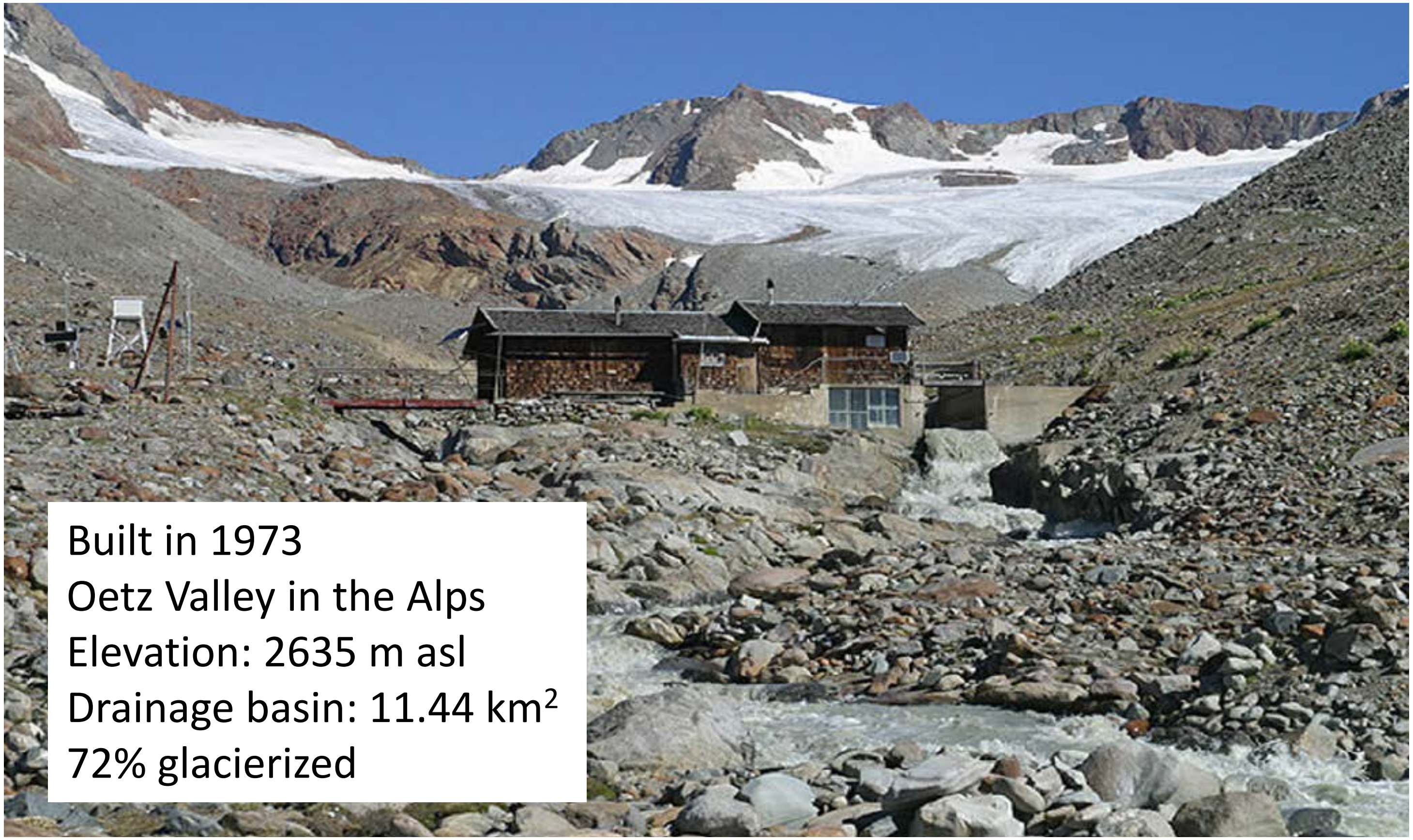
4. Examples

Vernagtbach gauging station

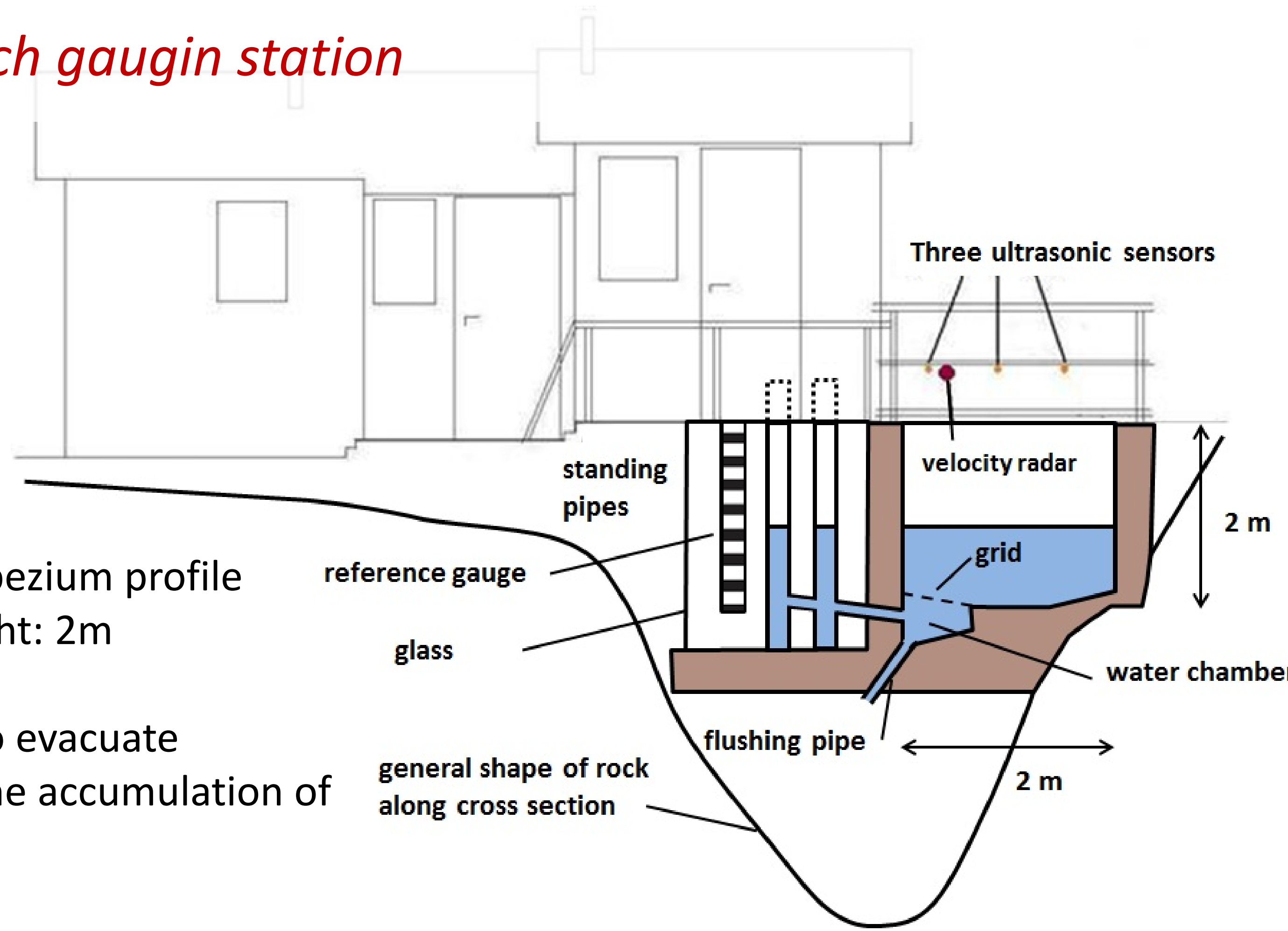


Built in 1973
Oetz Valley in the Alps
Elevation: 2635 m asl
Drainage basin: 11.44 km^2
72% glacierized

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

4. Examples

Vernagtbach gaugin station



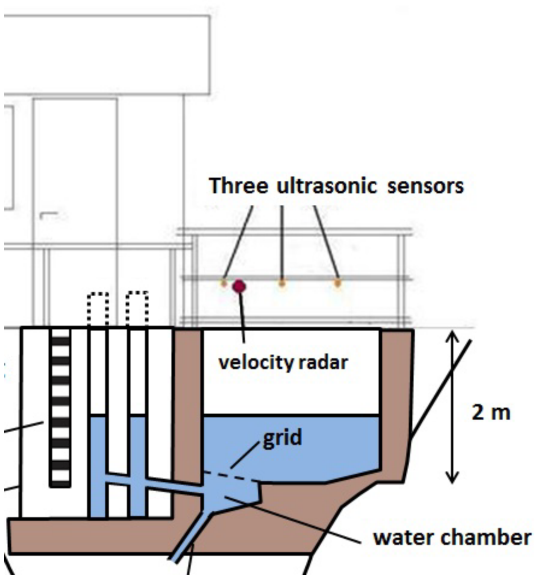
Channel of trapezium profile
width and height: 2m
length: 4.2m
flushing pipe to evacuate continuously the accumulation of sediment

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

4. Examples

Vernagtbach gaugin station

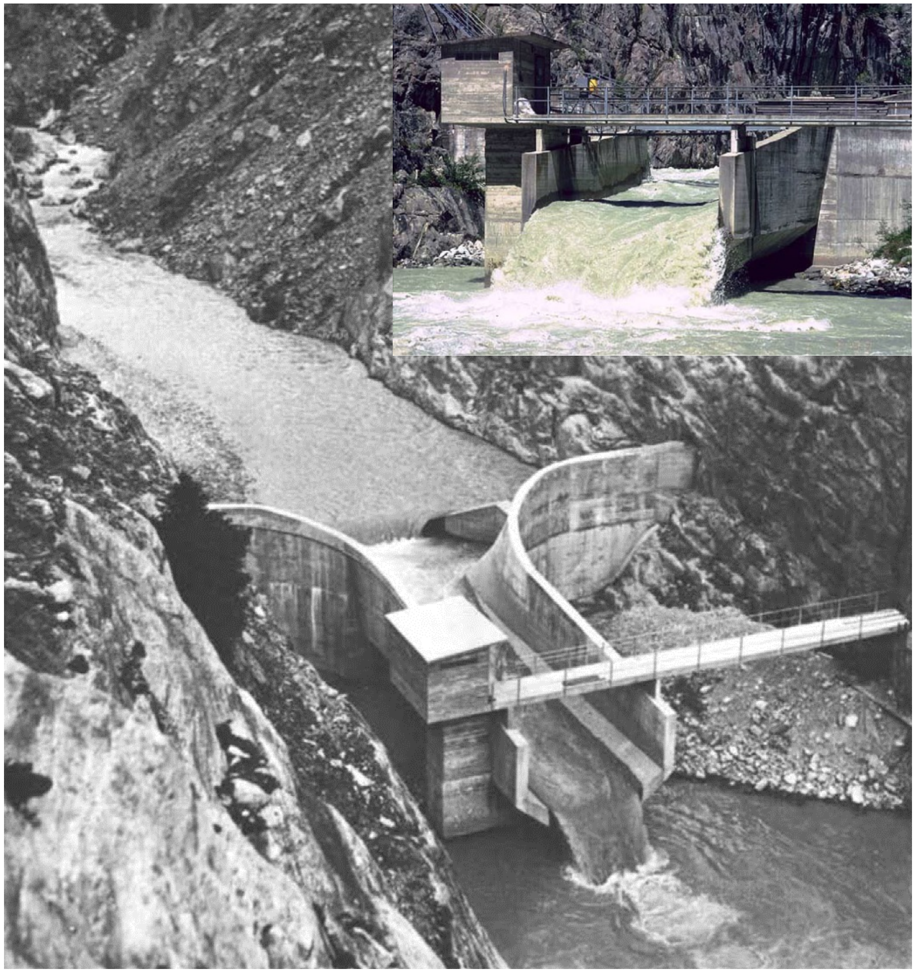
The measurement method is a combination of continuous recording of stage level and occasional measurements of discharge.

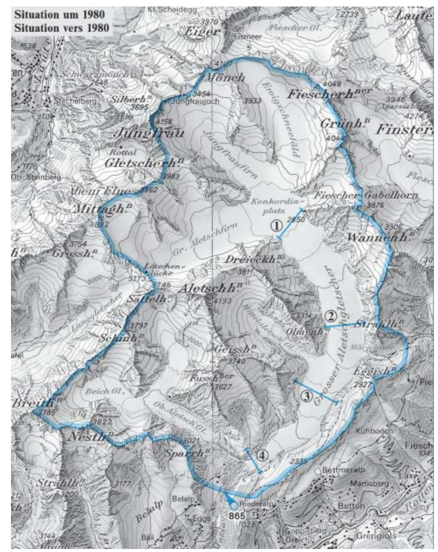


Sampling frequency	Technique
Momentary sampling	Integration (gulp) method with salt as a tracer (around 50 times a year)
Continuous automatic sampling	Water level measurements: • two communicating pipes and a float, connected to a stage recorder • three ultrasonic sensors

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

4. Examples




Situation um 1980
Situation vers 1980
Eiger
Mönch
Jungfrau
Konkordia-platz
Aletschh.
Dreieckh.
Wannenh.
Fiescherhörner
Gabelhorn
Riederalp
Bettmeralp
Fiesch
865

4. Examples

Exercise

You are interested in measuring discharge of the glacierized catchment of Chhota Shigri during an ablation period. Explain how you would measure it if you need daily or hourly measurements.
Which methods would you choose and why?
Which are the advantages or disadvantages of these methods?