Streamflow Measurements
Big Picture

• Why do we measure streamflow?
  Because is one of the most important topics in engineering hydrology directly related to water supply, flood control, reservoir design, navigation, irrigation, drainage, water quality, and others.

• How do we measure streamflow?

• Relating streamflow and stage?
Flow Measurements

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**USGS 13185000 BOISE RIVER NR TWIN SPRINGS ID**

- **DAILY Discharge**: cubic feet per second

**EXPLANATION**

- Median Daily Streamflow based on 93 years of record
- Measured Discharge
- Daily Mean Discharge
- Equipment malfunction

Provisional Data Subject to Revision
Measuring Discharge

- Velocity Meters
- Acoustic Doppler Current Profiler (ADCP)
- Weirs and Flumes
- Dilution Gaging
Mechanical velocity meters

- Measure velocity in one direction at a point
Mechanical velocity meters

- Measure velocity in one direction at a point.
Electromagnetic Velocity Meter
Measuring Velocity in Big Streams
Vertical Profile. Power Law

Turbulent Boundary Layer over a Smooth Flat Plate.

\( \frac{u}{U_\infty} = \left( \frac{y}{\delta} \right)^\frac{1}{7} \),

where \( \delta = \delta(x) \) to be determined. From equation (2):

\[ \delta^* = \frac{\delta}{\delta^*} \]

\[ \theta = \frac{7}{2} \delta \cong 0.0972 \delta \]

\[ \frac{\tau_\infty}{\rho U_\infty^2} = 0.0227 \left( \frac{U_\infty \delta}{\nu} \right)^{-\frac{1}{4}} \]

using another empirical formula for friction

(Blasius' law of friction) for pipes

Von Karman’s moment equation:

\[ \frac{\tau_\infty}{\rho U_\infty^2} = \frac{d}{dx} \left( \theta \right) \rightarrow 0.0227 \left( \frac{U_\infty \delta}{\nu} \right)^{-\frac{1}{4}} = \frac{7}{72} \frac{d \delta}{dx} \rightarrow \text{ODE for} \ \delta \]

\[ \frac{\delta}{x} \cong 0.373 R_x^{-\frac{1}{5}} \]

\[ \delta(x) \cong 0.373 x \left( \frac{U_\infty x}{\nu} \right)^{-\frac{1}{5}} \]

For \( \delta(0) = 0 \) and assuming turbulent boundary layer at \( x = 0 \), i.e., tripped at \( x = 0 \) or \( R_x >> 1 \),
Vertical Profile. Power Law

From:”” Power-law index for velocity profiles in open channel flows”. Nian-Sheng Cheng”, Advances in water resources, 2007

2.1. Power law

For uniform equilibrium flows in a wide open channel, the power law can be expressed in the following form:

$$\frac{u}{u_{\text{max}}} = \left(\frac{y}{h}\right)^{1/m}$$

where $u$ is the streamwise, time-mean flow velocity, $u_{\text{max}}$ is the maximum flow velocity taken at the free surface ($y = h$), $y$ is the bed-normal distance measured upwards from the profile datum, $h$ is the flow depth, and $1/m$ is referred to as the power-law exponent or index. In Eq. (1), the scaling parameters used are the maximum velocity and flow depth. If the power law is applied to the near-bed flow region only, $u_{\text{max}}$ can be replaced by the shear velocity $u_s$ and $h$ replaced by either the wall unit $v/u_s$ (where $v$ is the kinematic viscosity of fluid) for a smooth bed or the roughness height $k_s$ for a rough bed.

Empirically, the power-law index could be simply related to the friction factor $f$ for both smooth and rough pipe flows [7], yielding

$$m \sqrt{f} = C$$

where $C \approx 1.0$, and $f$ is defined as $8(u_s/U)^2$ with $U$ denoting the cross-section average velocity. Hinze [7] also reasoned that $C$ could be taken as 1.2 based on some other approximations. If applying both power and log law to the entire flow domain from the channel bed to free surface, it can be shown that $C = \sqrt{8\kappa}$, which equals 1.13 for $\kappa = 0.4$. This simple relation was previously used by Zimmermann and Kennedy [12] for approximating velocity distributions in meandering flows.

By extending his concept of incomplete similarity to wall-bounded turbulent flows, Barenblatt [13] argued that the power law was the sole correct scaling for mean flow velocity profiles.
Which Point to Use?
Vertical and Horizontal Variability

- 6/10\textsuperscript{th} method to measure average velocity for the vertical profile
- What about horizontal profile?
Acoustic Doppler Current Profiler (ADCP)

- Uses sound to measure 3D velocity at different depths
- Measures the velocity of the whole vertical profile at once
- Not just at one point as velocity meters do
Acoustic Doppler Current Profiler (ADCP)

Slide from Steve Lipscomb USGS-Boise
Discharge measurement using tethered ADCP and Riverboat

ADCP connected to laptop computer using radio modem

Riverboat with ADCP

Slide from Steve Lipscomb USGS-Boise
ADCP allows access for discharge and velocity measurements at remote sites

Slide from Steve Lipscomb USGS-Boise
ADCP allows access for discharge and velocity measurements at remote sites

Slide from Steve Lipscomb USGS-Boise
Screenshot of ADCP software showing discharge measurement of 6973 cfs in less than 5 minutes

Slide from Steve Lipscomb USGS-Boise
When water stages are measured, we need additional information to estimate the flow rates (or discharges).

- Stage Hydrograph
- Discharge Hydrograph
- Stage-Discharge Curve or Rating Curve

\[ Q = f(H) \]

\[ H = f(t) \]

\[ Q = f(Q) \]
• Typical relationship:

\[ Q = a(H + b)^c \]

• Or also:

\[ Q = a \ (h - h_0)^b \]
Rating Curve

- Typical relationship: $Q = a(H + b)^c$
- The function relationship between $H$ & $Q$ has to be calibrated locally for different stations.

FIGURE 8.3.7 Rating curve for Grey River at Dobson, New Zealand. The stage-discharge rating (a) is extrapolated after extending curves through the stage-area (b) and stage-velocity (c) data to the maximum recorded stage of 20.4 ft. The extrapolated rating curve in (a) is drawn through points of area $\times$ mean velocity, read from curves (b) and (c). Note that departure from the rating curve of the gauging marked $A$ can be attributed to an incorrect mean velocity in (c).
Gaging Stations
Measurement of Stream Flow

Mid-Section Method

\[ A_i = b d_i \]
\[ Q_i = \overline{V_i} A_i \]
\[ Q = \sum_{i} Q_i = \sum_{i} \overline{V_i} A_i \]
Measurement of Stream Flow

Mean-Section Method

\[ A_i = \frac{b}{2} (d_i + d_{i+1}) \]

\[ \bar{V}_i = \frac{1}{2} (\bar{V}_i + \bar{V}_{i+1}) \]

\[ Q_i = \bar{V}_i A_i \]

\[ Q = \sum_{i} Q_i \]
Measurement of Stream Flow

Mean-Section Method

\[ A_i = \frac{b}{2} (d_i + d_{i+1}) \]

\[ \bar{V}_i = \frac{1}{2} (\bar{V}_i + \bar{V}_{i+1}) \]

\[ Q_i = \bar{V}_i A_i \]

\[ Q = \sum Q_i \]

\[ V_i = \text{mean of velocities at 0.2 and 0.8 depth} \]

\[ v_i = \frac{v20_i + v80_i}{2} \]
Measurement of Stream Flow

free surface velocity

When:
Velocity and flow depth too high
Velocity too low
Floating debris

\[ V = c \frac{L}{t} \]

measure the transit time \( t \) of a floating body, distance \( L \)

Reduction coefficient \( c \ 0.5-1 \) (typically obtained by means of current meters)

Multiple measurements to reduce errors …

UNI748:2003
La norma UNI748:2003 prevede:

- Si devono scegliere tre sezioni trasversali perpendicolari alla direzione del flusso lungo il tronco di canale (inizio, metà e fine).
- La distanza tra le sezioni trasversali dovrebbe essere almeno il doppio della larghezza del canale.
- Le sezioni trasversali devono essere abbastanza distanti eccetto per il tempo impiegato dai galleggianti per passare da una sezione alla successiva che deve essere misurata accuratamente.
- Le sezioni trasversali intermedie devono essere utilizzate solo per controllare la misura delle velocità tra le sezioni trasversali all’inizio ed alla fine del tronco di canale.
- Si raccomanda una durata minima di 20 s per lo spostamento del galleggiante.
- Il galleggiante deve essere rilasciato abbastanza distante al di sopra della prima sezione in modo da attraversarla dopo aver raggiunto una velocità costante.
- Le distanze del galleggiante dalla sponda mentre passa ogni sezione trasversale possono essere determinate con idonei mezzi ottici (es. toedolite).

\[ V = c \frac{L}{t} \]

- \( t \) = tempo di percorrenza (da misurare)
- \( L \) = lunghezza del tratto
- \( c \) = fattore correttivo (0,6 – 1)
Measurement of Stream Flow

**Area-Slope Method**

By Manning formula:

\[ Q = \bar{K} \left( \frac{S_f}{2} \right)^{1/2} = \bar{K} \left( \frac{h_L}{L} \right)^{1/2} \]

where

\[ \bar{K} = \left( K_1 \times K_2 \right)^{1/2} \]

\[ K_i = \frac{1}{n_i} \left( A_i R_i \right)^{2/3}, \ i = 1, 2 \]

\( K_1 \neq K_2 \) if flow cross-section is not uniform, minor loss should be subtracted from \( h_L \).
Extension of Rating Curve

- During the event of large flood, it is impossible or impractical to measure discharge directly. More often than not, the flood stage goes beyond the range of the data range used to define the rating curve. Therefore, extrapolation of the rating curve is needed when water level is recorded below the lowest or above the highest level.
- Large errors can result if the functional form of rating curve, \( Q = a \times (H+b)^c \), is extrapolated beyond the recorded gauge discharges without consideration of the cross-section geometry and controls.
- Graphical extension or by the fitted Q-H relationship is adequate only for small extension.
- For large extrapolation beyond the active channel cross-section, hydraulic formula can be used to estimate the stage-discharge relation.
Problems with the Rating Curve Approach

At very low flows in wide shallow streams, it is difficult to make accurate velocity measurements. The relationship between depth and flow is often different depending upon whether flow is increasing or decreasing. This is sometimes called hysteresis in the stage-discharge curve because the relationship depends on the recent history of measurement. This is caused by there being higher velocities in rising flow and lower velocities in declining flow. When hysteresis leads to large errors, it can be addressed by measuring depth at two different locations and the rating curve becomes a function of both depth at one location and the difference in depth at the two locations.

In rivers affected by tides, or backflow from larger rivers it is also necessary to measure depth at two different points to correct for the influence of these effects.
Problems with the Rating Curve Approach

Rating curves may change when significant change occurs in the geometry of the stream channel or if an obstruction to flow is introduced or removed. Log jams, ice jams, beaver dams may cause temporary deviations from a rating curve. Erosion of streambed or banks, sediment deposition, stream dredging or major construction in a stream or flood plain can cause permanent changes in a rating curve and a new rating curve may need to be established.

In order to avoid frequent changes in rating curves from erosion or deposition, USGS attempts to locate flow gauging stations in places where the streams are relatively stable.
Weirs

- Have a more definite relationship between stage and flow
- Higher accuracy than velocity X-sections
- Only can be used for smaller streams

(Norme UNI 6871-71P)
Weirs
Weirs

In prima approssimazione:

\[ Q = C_q \sqrt{2g} \ h_0^{3/2} b \approx 1.81 \ h_0^{3/2} b \]

\( C_q = \) coefficiente di efflusso pari a 0.41
Weirs

\[ Q = 1.42 \cdot h_0^{3/2} \]

Indicato per la misura di piccole portate

Esempio di stramazzo triangolare utilizzato per la misura dei deflussi in un piccolo corso d’acqua montano
Weirs

\[ Q = A \cdot V = C_q \ h_0^{3/2} \ b \ \sqrt{2g} \]

- \( Q \) – portata (m³ s⁻¹)
- \( A \) – sezione liquida (m²)
- \( V \) – velocità della corrente (m s⁻¹)
- \( C_q \) – coefficiente di efflusso, dipende dalla geometria dello stramazzo (adim)
- \( h_0 \) – carico sullo stramazzo (m)
- \( b \) – larghezza dello stramazzo (m)
- \( g \) – accelerazione di gravità (9.81 m s⁻²)

Alcuni esempi di coefficiente di efflusso:

- Rettangolare a parete sottile
  \[ Q = 0.410 \ h_0^{3/2} \ b \ \sqrt{2g} = 1.810 \ h_0^{3/2} \ b \]

- Bélanger a parete grossa
  \[ Q = 0.385 \ h_0^{3/2} \ b \ \sqrt{2g} = 1.705 \ h_0^{3/2} \ b \]

- Thomson – V 90°
  \[ Q = 0.320 \ h_0^{3/2} \ \sqrt{2g} = 1.420 \ h_0^{3/2} \]
Weirs
Sharp-Crested rectangular Notch Weirs

• \( Q = C_d \, LH^{3/2} \)

• \( Q = \) discharge cfs
• \( C_d = \) coefficient
• \( L = \) Width of notch feet
• \( H = \) Depth of flow feet
Broad Crested Weir

[Diagram showing a broad crested weir with labels for H, Y, y_c, L, and V_1]
Flumes (italian: canale artificiale)

- Have relationship between stage and flow defined by hydraulics of the flume
- Higher accuracy than velocity X-sections
- Only can be used for smaller streams
- Measure water surface at two points in flume to calculate flow
Flumes (Italian: canale artificiale)
Ultrasonic methods
Ultrasonic methods

UNI EN ISO 748-2003 Measurement Of Liquid Flow In Open Channels - Velocity-area Methods

Standard Number: UNI EN ISO 748-2003
Title: Measurement Of Liquid Flow In Open Channels - Velocity-area Methods
Language: Italian
Replaced by Standard: UNI EN ISO 748-2008 Hydrometry - Measurement of liquid flow in open channels using current-meters or floats Idrometria - Misurazione della portata di liquidi in canali aperti mediante correntometri o galleggianti

Adopted International Standard: NEN EN ISO 748-2007
Hydrometry - Measurement Of Liquid Flow In Open Channels Using Current-meters Or Floats Identical
SS EN ISO 748 Ed. 2 (2007)
Status: Withdrawn
International Classification for Standards (ICS): METROLOGY AND MEASUREMENT. PHYSICAL PHENOMENA >> Measurement of fluid flow >> Flow in open channels
Publisher: Unificazione Italiana (UNI)
Description: Defines methods for determining the velocity and cross-sectional area of water flowing in open channels without ice cover, and for computing the discharge therefrom. It also covers methods of employing current-meters or floats to measure the velocities.
Ultrasonic methods

Correlation method

Doppler method

Transit time Method
Ultrasonic methods
Dilution Gaging

• Useful for small streams and streams with lots of boulders, wood, or other roughness elements

• Some limitations on the size of the stream to be measured
Constant Injection
Constant Injection

\[ Q_1 C_1 = Q_2 C_2 \]

- Inject tracer with a known concentration \((C_1)\) at a known flow rate \((Q_1)\) into the stream
- Measure the stream concentration \((C_2)\) after complete mixing
- Calculate the stream flow \(Q_2 = (Q_1 C_1)/C_2\)
Slug Injection

- Peak
- Tail
Slug Injection

- Dump a known mass of tracer into the stream
- Measure the whole peak after mixing downstream
- Calculate discharge $Q = \frac{\text{Mass}}{\text{Area under Curve}}$

$$Q = \frac{M}{\int \bar{C(t)}dt}$$

$\bar{C}(t) = \text{Average concentration in the cross section}$
Slug Injection
Slug Injection
Slug Injection
Slug Injection

\[ Q = \frac{M}{\int C(t)dt} \]
Slug Injection
Slug Injection
Slug Injection
Hydrology for Hydropower
References

- Keith J. Beven, Rainfall - Runoff Modelling: The Primer, John Wiley & Sons, Chichester, UK
Main processes to be modeled

Components of the hydrological cycle

- Precipitation (R)
- Snow cover
- Infiltration
- Deep infiltration
- Deep percolation
- Groundwater
- Surface runoff
- Subsurface runoff
- Return flow
- SW-GW exchange
Modeling as a Management tool

• Steps to build a hydrological model
  – Conceptual model (decide what we want to model)
  – Mathematical model (problem dimensionality and code selection)
  – Catchment characterization
  – Field data collection
  – Input data preparation
  – Sensitivity analysis and calibration
  – Predictive runs
  – Uncertainty analysis

• Reporting the modeling effort
• Post-auditing
Parts of Hydrological model

- **Precipitation and snow module**
  - Spatial interpolation
  - Solid or liquid precipitation?
  - Snow-accumulation and melting

- **Soil water dynamic module**
  - Interception
  - Infiltration
  - Evapotranspiration

- **Streamflow generation module**
  - Hillslope (fast and slow stormflows)
  - Routing in the river network
Spatial and Temporal scales

Several spatial and temporal scales are present and involve physical, chemical, biological and ecological processes.

Different components can be relevant or not depending on the selected time scale (e.g. at flood event scale: evapotranspiration and runoff).
Catchment delineation: GIS analysis…. again!!
Data needs

DEM (Digital Elevation Map)

Technical maps for the identification of outlet and main nodes (e.g. Pellizzano)
Software

GRASS (Linux/Unix)

JGRASS (Windows)

ARCgis, ARCVIEW with package Hec-GeoHMS (Windows)
Objectives

• Catchment identification at the outlet.
• Subdivision in sub-catchments where the hydrological modeling will be applied. Different contribution will then be summed up in order to obtain the overall response of the system.
• Reconstruction of river network topology.
• Identification of sub-catchments centroid, area and length of main channel.
Identification of catchment outlet

Noce river basin

Pellizzano drainage area
Output maps

Drainage directions

Sub-catchments subdivision
Output maps

River network structure

Each stream is associated to a pertaining hillslope
| Numero di Sottobacini: 27 |

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Can we skip all these preliminary analyses and all the modeling?

…..It depends, if the focus is only on peak estimation yes, but the results are really uncertain → Envelops curves
Envelop curves

Peak flow estimation

\[ Q_{\text{max}} = q_{\text{max}}S \quad S \left[ km^2 \right]; \quad q_{\text{max}} \left[ m^3 / s \ km^2 \right] \]

Regionalization approach based on experimental observation:

\[ q_{\text{max}} = \frac{a}{S + b} + c \left[ m^3 / s \ km^2 \right] \]

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<td>De Marchi (400 mm in 12h)</td>
<td>3000</td>
<td>125</td>
<td>5</td>
<td>S≤150 km²</td>
</tr>
<tr>
<td>Scimemi</td>
<td>600</td>
<td>10</td>
<td>1</td>
<td>S≤1000 km²</td>
</tr>
<tr>
<td>Pagliaro</td>
<td>2900</td>
<td>90</td>
<td>90</td>
<td>S≤1000 km²</td>
</tr>
</tbody>
</table>
Envelop curves

$\max (m^3/s \ km^2)$

- Pagliaro
- Scimemi
- Forti
Envelop curves

Other formulations:

\[ q_{\text{max}} = c \ S^n \]

Gherardelli [1939]
\[ q_{\text{max}} = q_{100} \ \frac{S}{100} \]

\[ q_{100} = 2.8 \quad 20.5; \quad n = 0.7 \quad \text{Bacini impermeabili} \]

\[ q_{100} = 0.2 \quad 9.5; \quad n = 0.5 \quad \text{Bacini permeabili} \]

Marchetti [1955]
\[ q_{\text{max}} = q_{100} \ \frac{S^{2/3}}{100} \]

\[ q_{100} = 0.4 \quad 19.8; \quad \text{Bacini impermeabili} \]

\[ q_{100} = 0.2 \quad 13.6; \quad \text{Bacini permeabili} \]
Maximum specific discharge as a function of catchment area. Continuous lines denote marchetti formula with two different values of $q_{100}$, dal libro: U. Maione, Le piene Fluviali, (seconda edizione) La Goliardica Pavese, 1995
Curve di inviluppo (continua)

Formula di Mongiardini (1948): introduce, seppure in modo approssimato, la dipendenza della portata dalla precipitazione

\[ q_{100} = k_r c h \]

*h*: indice di piovosità [mm;] \( h = \frac{P}{nd} \), nella quale \( P \) è la media della precipitazione annuale e \( nd \) è il numero medio di giorni piovosi

c*: coefficiente di deflusso medio

Mongiardini ha diviso il territorio nazionale in 32 regioni per ciascuna delle quali ha fornito il valore del coefficiente \( k_r \) (variabile da 0.5 a 3.3)

- Bacini veneti e lombardi: bacini impermeabili fra l’Adige ed il Ticino: \( k_r = 0.5 \) (0.78 considerando anche la piena eccezionale del Ticino a Sesto Calende del 1868);
- Bacini permeabili compresi fra l’Isonzo ed il Brenta: \( k_r = 0.83 \)
**Formula di Tonini (1939)**

- Esprime la portata al colmo della piena in funzione del tempo di ritorno $T$

\[
u(T) = \frac{Q_{\text{max}}}{S} = C_p S^{0.2} (1 + 68 S^{0.5})(1 + 1.18 \log_{10} T)
\]

$C_p$: coefficiente di piena che dipende dal bacino

La formula proposta da Tonini deriva dall’analoga formulazione proposta da Fuller:

\[
u(T) = \frac{Q_{\text{max}}}{S} = C_p S^{0.2} (1 + 2.66 S^{0.3})(1 + 0.8 \log_{10} T)
\]
Formula di Tonini (continua)

Alcuni valori del coefficiente di piena

<table>
<thead>
<tr>
<th>Corso d'acqua</th>
<th>Stazione</th>
<th>Superficie S (km²)</th>
<th>C_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brenta</td>
<td>Sarson</td>
<td>1562</td>
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<tr>
<td>Noce</td>
<td>Dermulo</td>
<td>1056</td>
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<tr>
<td>Adige</td>
<td>Pescantina</td>
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<td>0.52</td>
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<tr>
<td>Adige</td>
<td>Trento</td>
<td>9761</td>
<td>0.51</td>
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<tr>
<td>Adige</td>
<td>Boara Pisani</td>
<td>11954</td>
<td>0.49</td>
</tr>
<tr>
<td>Po</td>
<td>Pontelagoscuro</td>
<td>70091</td>
<td>0.62</td>
</tr>
</tbody>
</table>


Adige a Trento: 2677 m³/s; Po a Pontelagoscuro: 19703 m³/s Per T=100 anni