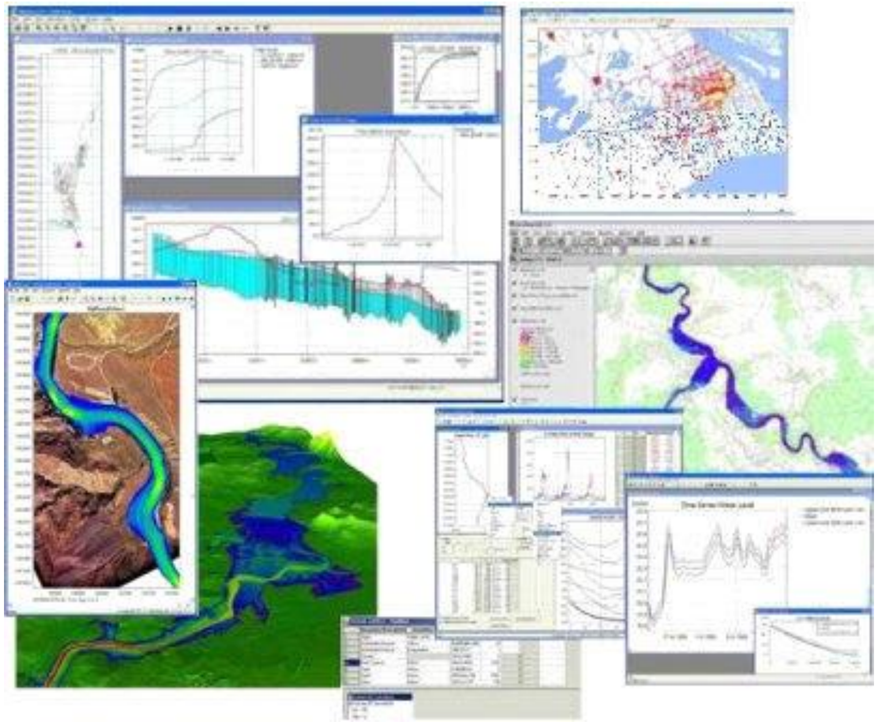
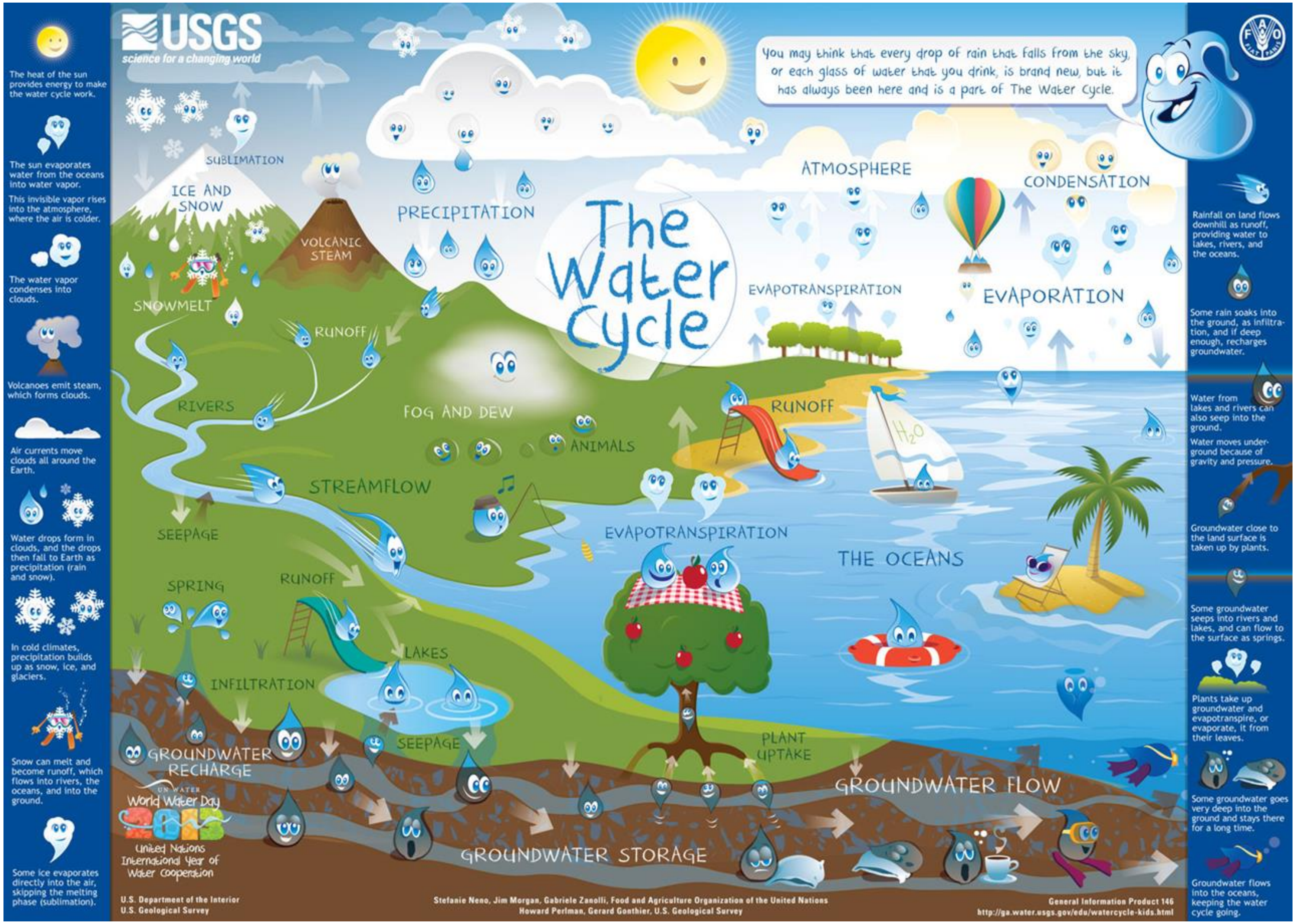
Numerical Simulation - Free Surface Flow



River Modelling

River: Part of the Water Cyle



River - Term Specification

What is a River ?

- no standard definition
- “A **stream** is a body of water[1] with a **current**, confined within a **bed** and **stream banks**. Depending on its location or certain characteristics, a stream may be referred to as a branch, brook, beck, burn, creek, crick, gill (occasionally ghyll), kill, lick, mill race, rill, **river**, syke, bayou, rivulet, streamage, wash, run, or runnel.”
- “A **river** is a natural flowing **watercourse**, usually freshwater, flowing towards an ocean, sea, lake or another river”

reference: wikipedia

River Characteristics

Typical Properties

- bed with left and right banks (in direction of flow)
- filled by water (permanent / temporary)
- water level can change by time
- water has a dominant flow/current (time depending)
- flow is mainly induced by gravitation forces
  -> slope from upstream to downstream
- spring (upstream)
- mouth (downstream) to river, lake, sea
- tributaries -> river network

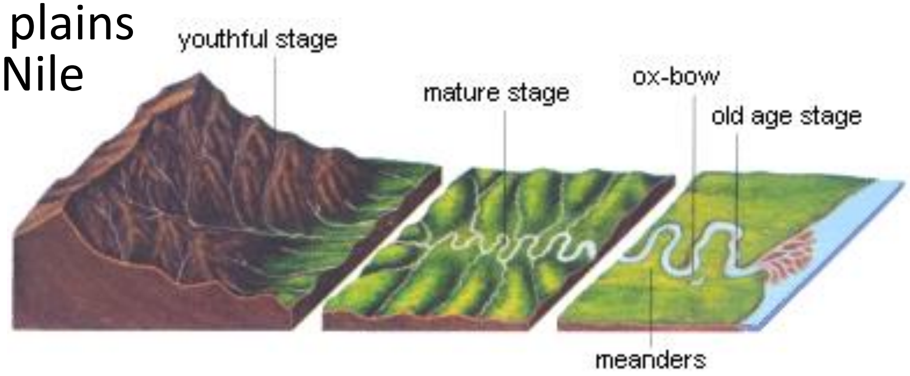
Rivers: Examples

River	Length (km)	Area (km²)	Av. Q (m³/s)
Nile	6852	3255000	2660
Amazon	6448	6112000	206000
Yangtze	6380	1722000	31900
Mississippi	6051	2980000	18400
Volga	3530	1360000	8064
Danube	2857	817000	6700
Rhine	**1239**	**218300**	**2900**
Spree	**382**	**9793**	**36**
Var	114	2819	50
Estéron	66	451	7

River Classification

Topographical classification

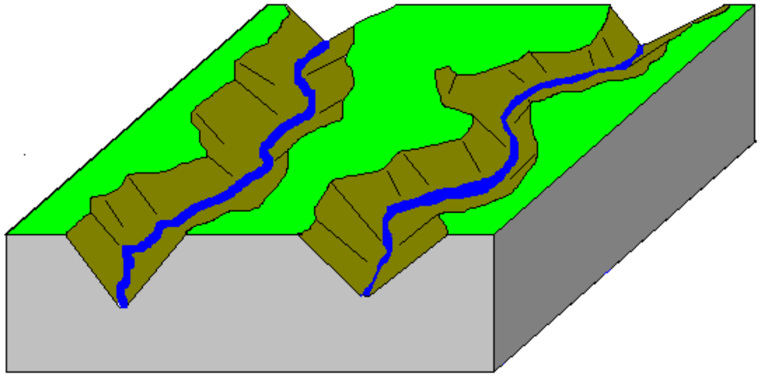
- **Youthful river**
  steep gradient, very few tributaries, quick flow
  channel erodes deeper rather than wider
  Brazos, Trinity, Ebro
- **Mature river**
  less steep gradient, many tributaries, more slowly flow
  more discharge than a youthful river
  channel erodes wider rather than deeper
  Mississippi, Danube, Ohio, Thames
- **Old river**
  low gradient, low erosive energy, flood plains
  Yellow river, Ganges, Tigris, Euphrates, Nile
- **Rejuvenated river**
  gradient raised by tectonic uplift
  Rio Grande, Colorado River

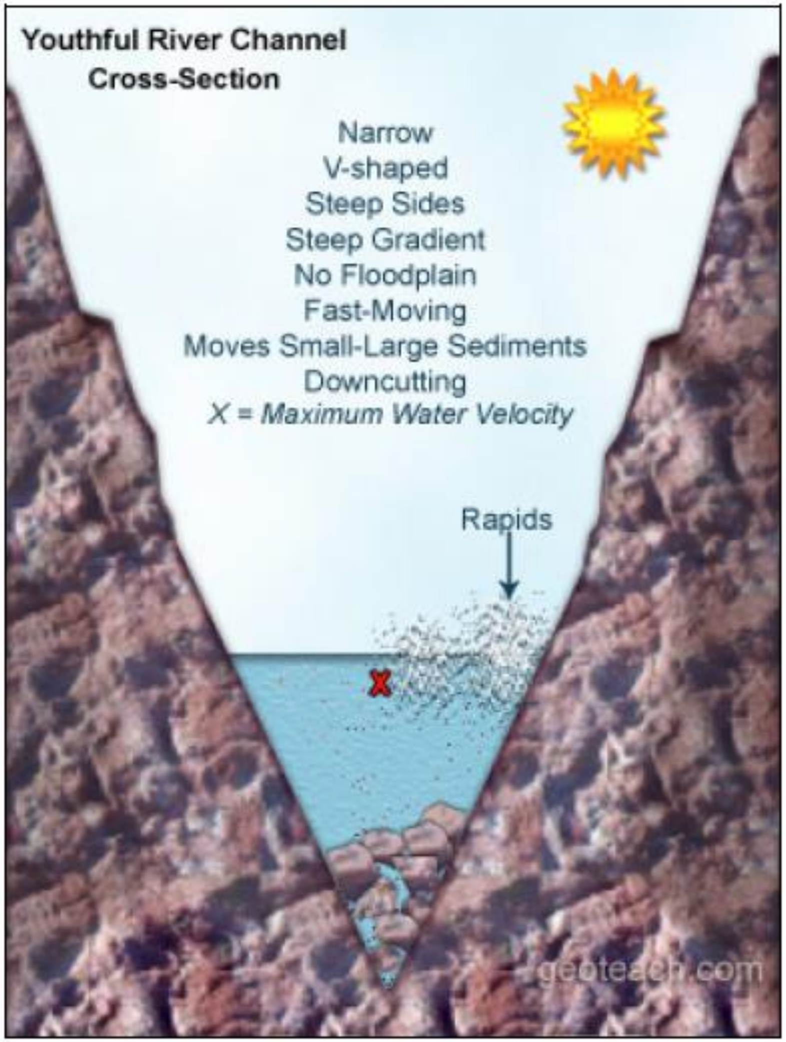


River Classification

Topographical classification

- **Youthful river**
  steep gradient
  very few tributaries
  no floodplains
  quick flow
  channel erodes deeper rather than wider
  examples: Brazos, Trinity, Ebro



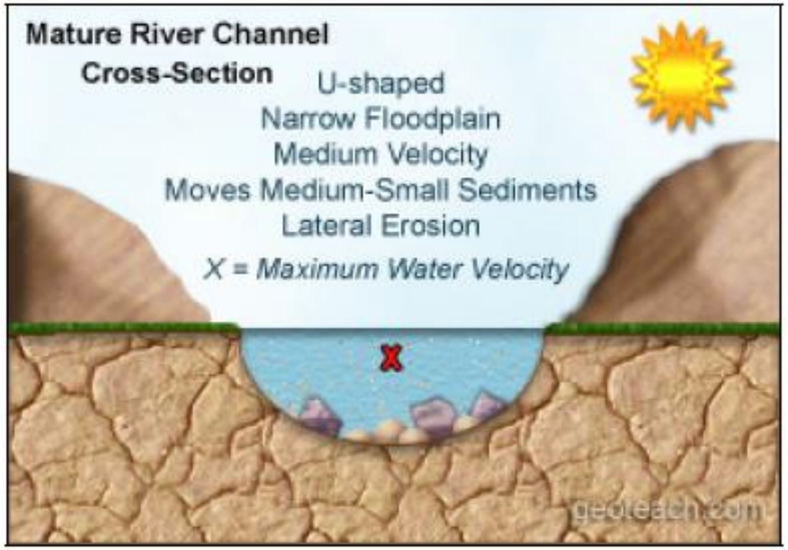


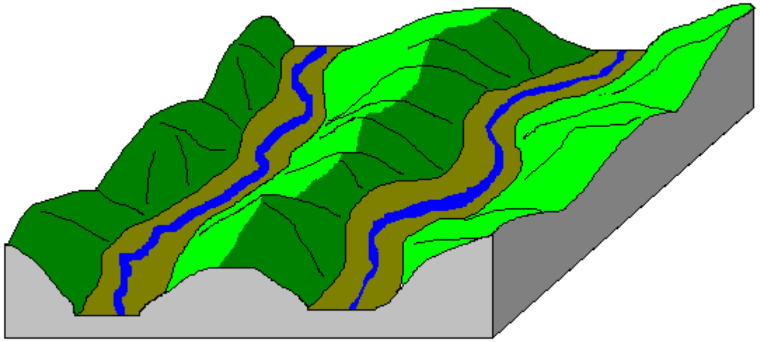
reference: Immoor Geoterach.com

River Classification

Topographical classification

- **Mature river**
  less steep gradient
  many tributaries
  more slowly flow
  more discharge than a youthful river
  channel erodes wider rather than deeper
  examples: Mississippi, Danube, Thames



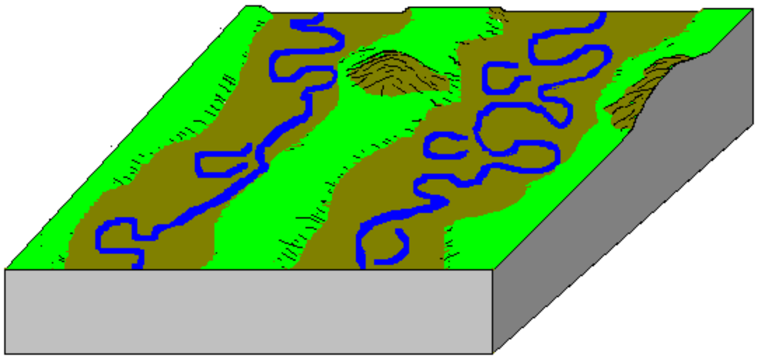


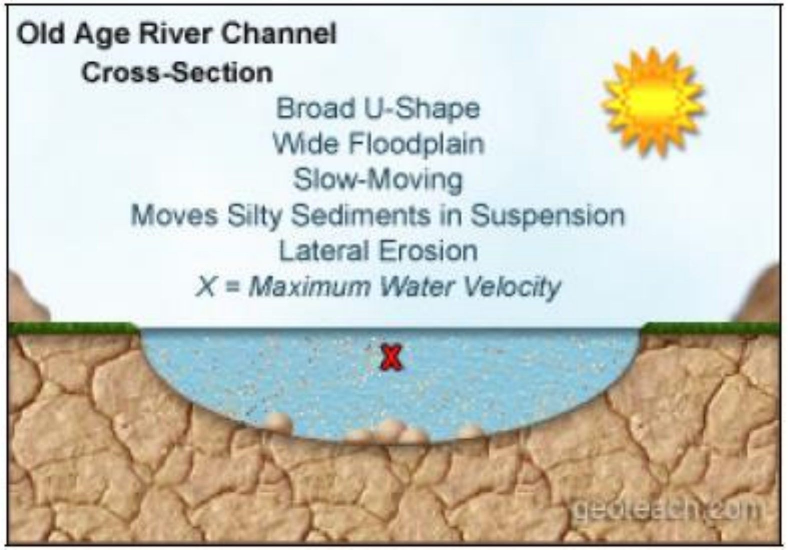
reference: Immoor Geoterach.com

River Classification

Topographical classification

- **Old river**
  low gradient
  low flow
  low erosive energy
  wide flood plains
  examples: Yellow river, Ganges,
  Tigris, Euphrates, Nile



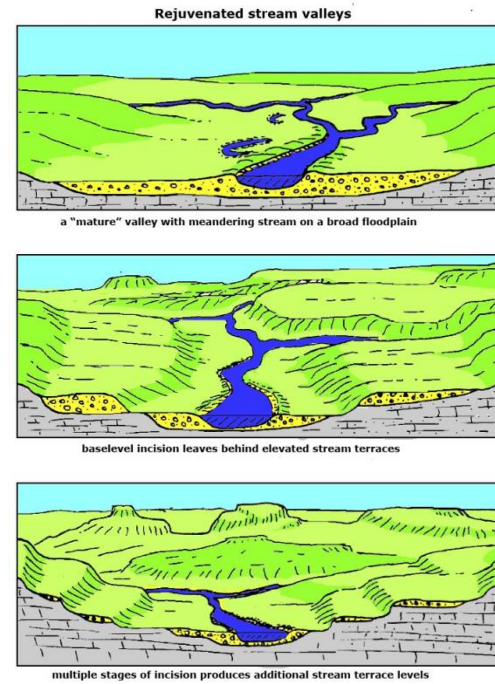


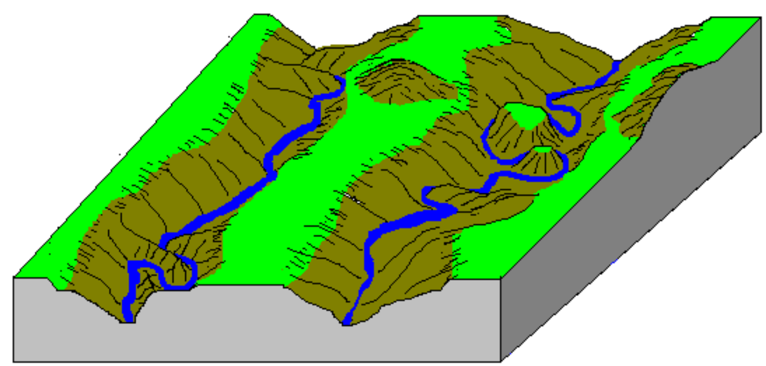
reference: Immoor Geoterach.com

River Classification

Topographical classification

- **Rejuvenated river**
  gradient raised by tectonic uplift
  examples: Rio Grande, Colorado River





River Classification

Morphological classification

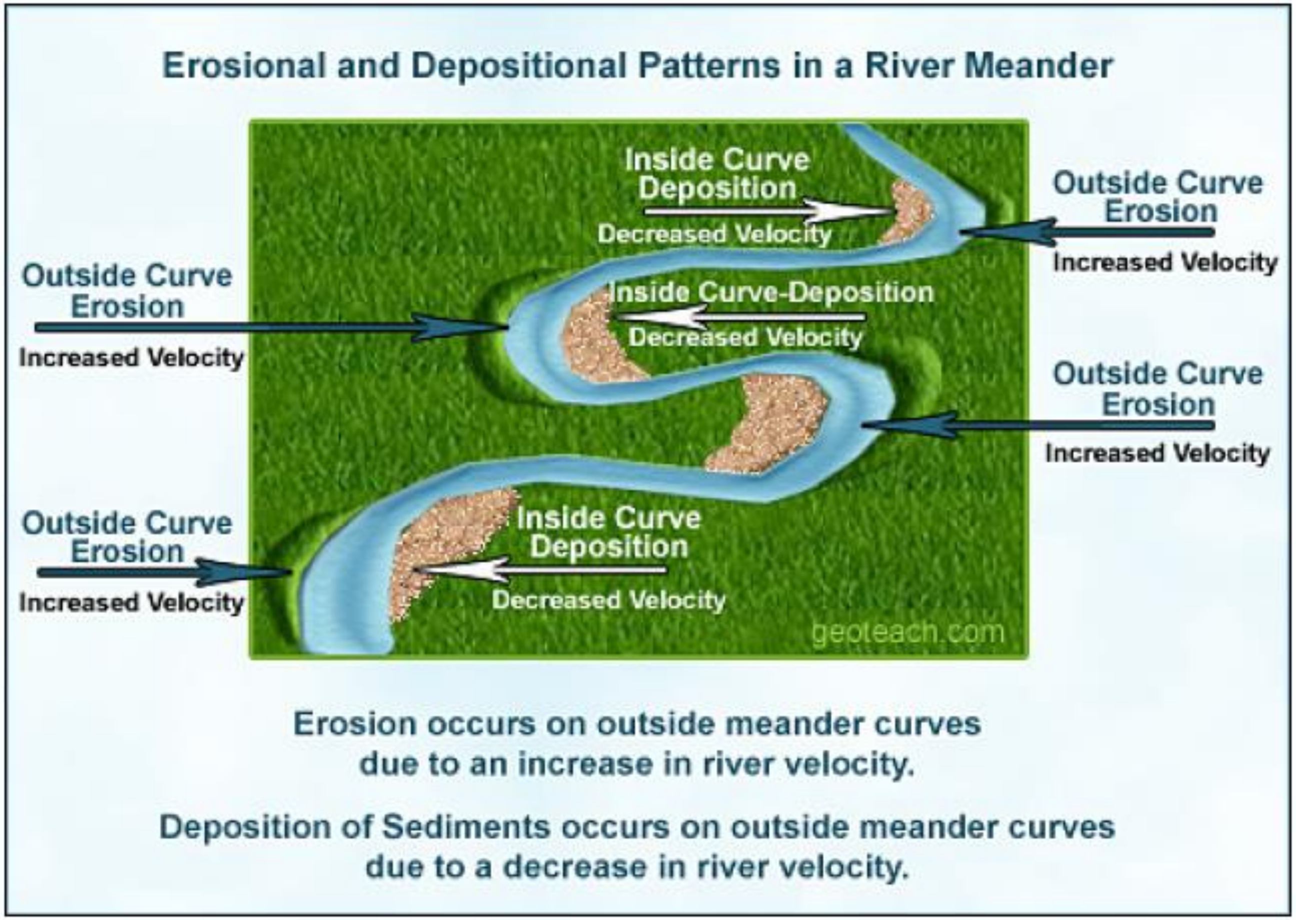
- straight river
- braided river
- meandering river

River Morphodynamics

River Sediment

River Morphodynamics

Sediment Transport

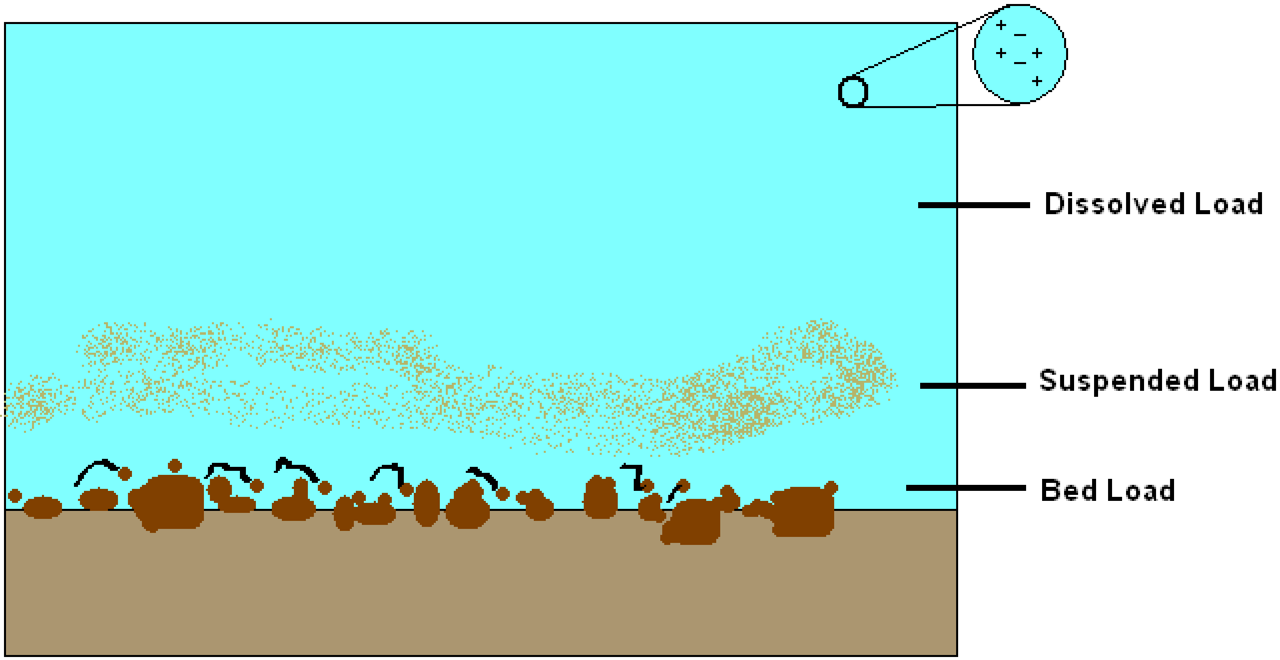


reference: Immoor Geoterach.com

River Classification

Sediment Transport

- wash load
- dissolved load
- suspended load
- bed load



-> Rouse Number

$$P = \frac{w_s}{\beta K u_*}$$

fall velocity / shear velocity
von Karman constant
turbulence

Mode of Transport	Rouse Number
Bed load	> 2.5
Suspended load: 50% Suspended	> 1.2, < 2.5
Suspended load: 100% Suspended	> 0.8, < 1.2
Wash load	< 0.8

River Engineering

What is River Engineering ?

- process of planned and performed human intervention
  in the course, characteristics, or flow of a river
  with the intention of managing the river in a beneficial way
- temporary intervention
  -> e.g. dredging
- permanent interventions
  -> e.g. construction in the river bed or at the river bank

no management without engineering!

River Engineering

Why River Engineering ?

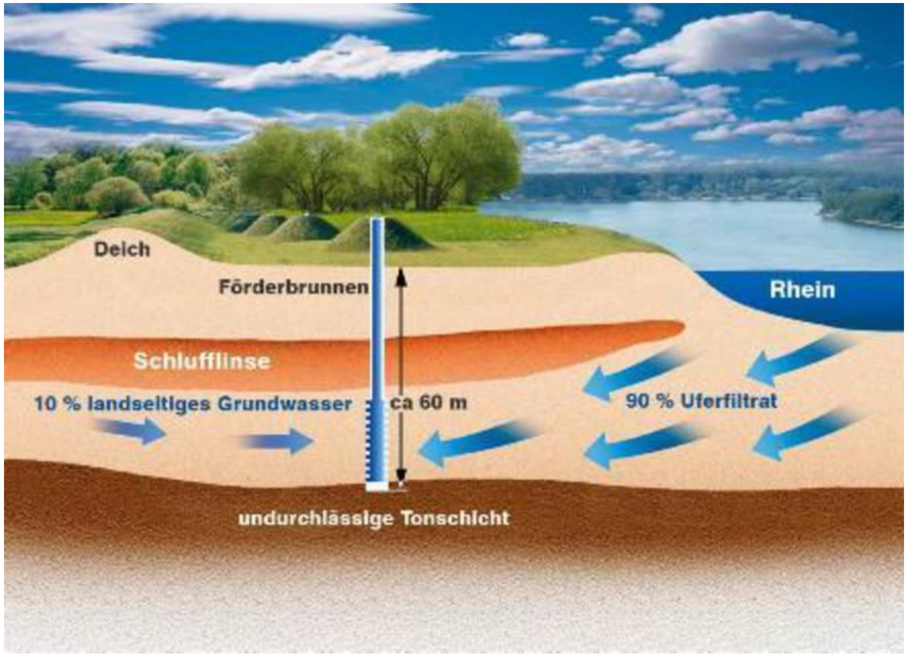
- water supply and drainage
  -> drinking water reservoirs
  -> wells, bank filtration
- flood protection and management
  -> detention reservoirs
  -> dams, protection walls
- navigation
  -> locks, navigation channels
  -> harbours
- energy production
  -> hydropower stations
  -> pumped hydroelectric energy storage
  -> cooling for power stations (e.g. nuclear power stations)
- …

River Engineering

Drinking Water Reservoirs

River Engineering

Bank Filtration: Drinking Water



River Engineering

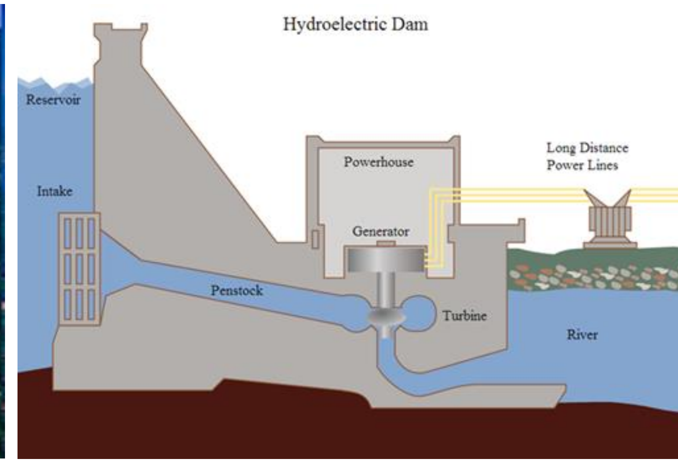
Flood Protection and Management

River Engineering

Navigation

River Engineering

Water Management / Energy Production



River Engineering

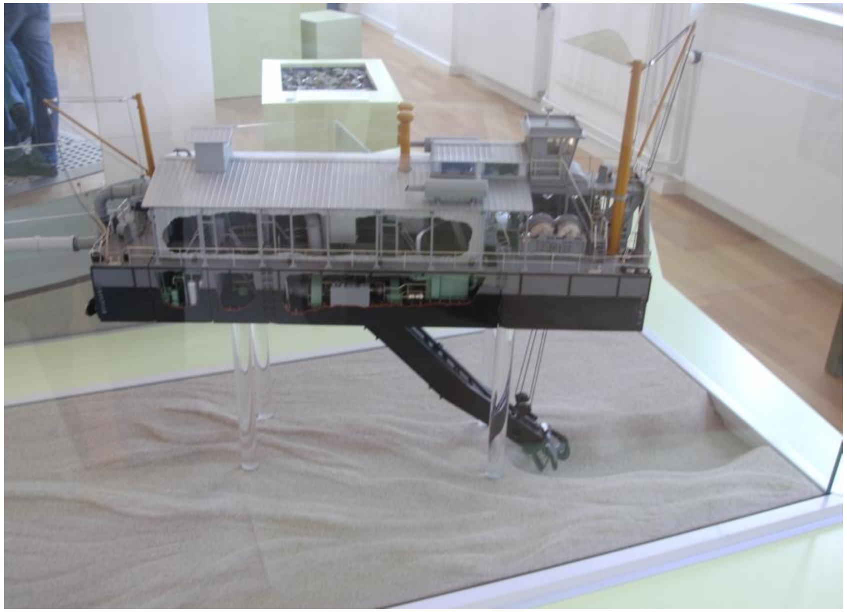
Energy Production

River Engineering

Dredging

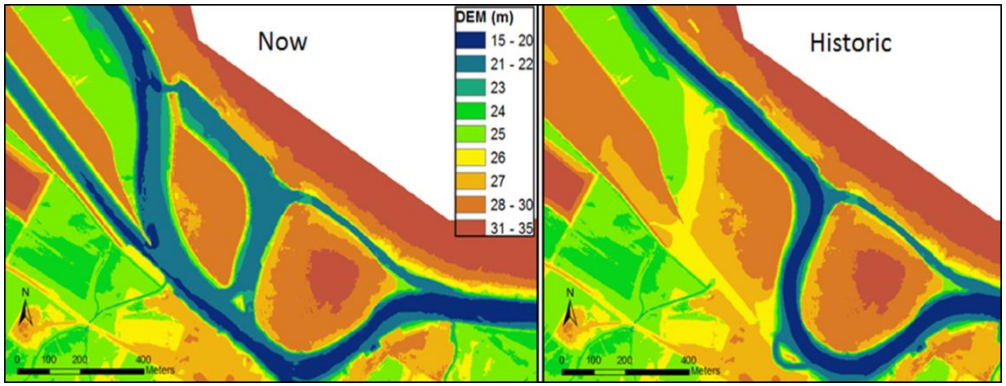
River Engineering

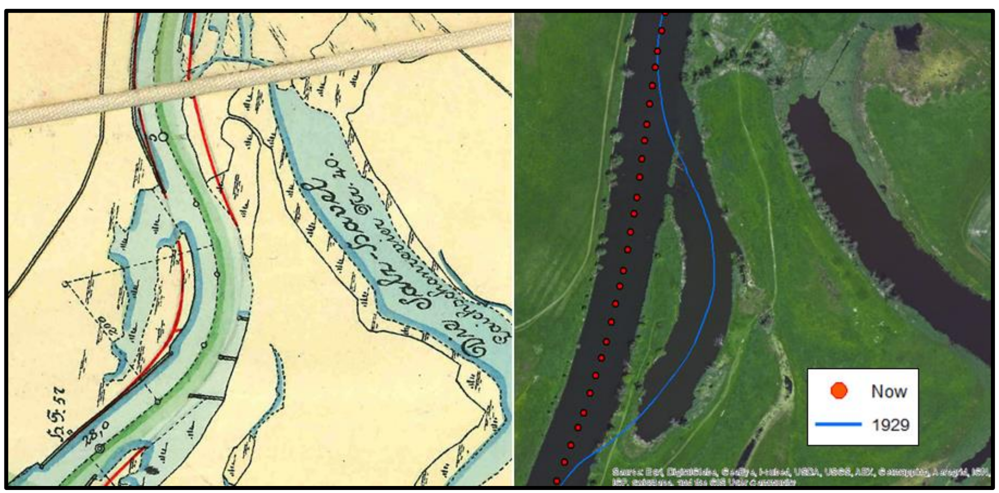
Dredging

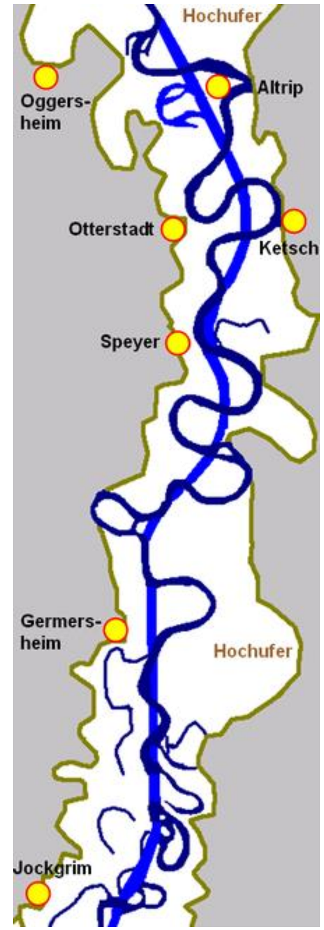


River Engineering

Stream Straightening, Canalization and Renaturation







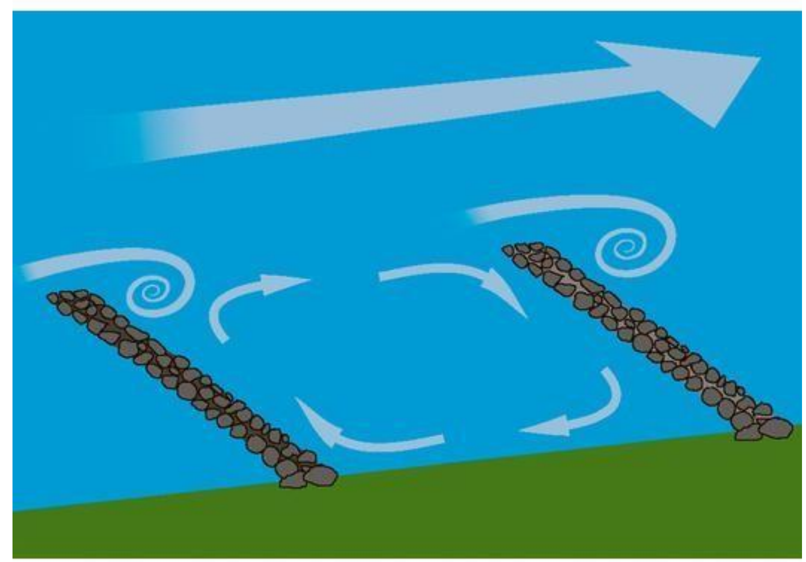
River Engineering

Examples Constructions

- reservoires
- groynes
- weirs
- culvert
- locks
- bank protection
- dams and dikes
- …

River Engineering

Construction: Groynes



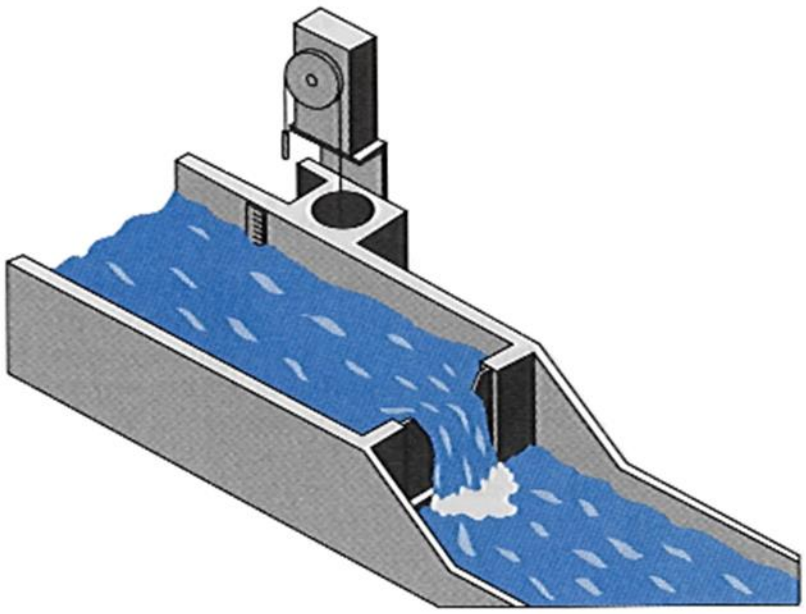
River Engineering

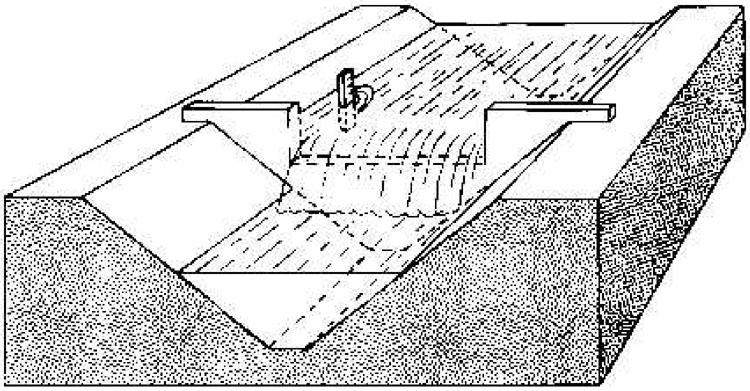
Construction: Weir

to manage the flow

- weir equation $Q = C\ L\ H^n$

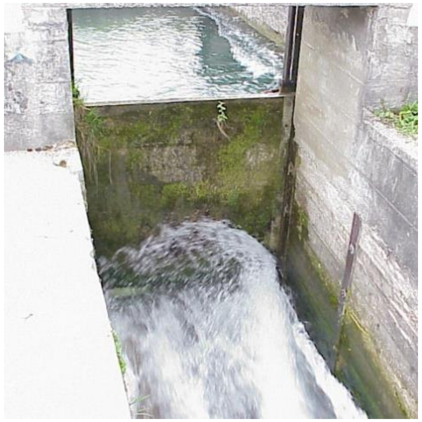
  Q = discharge
  C = weir parameter -> empiric value
  L = length of the crest
  H = water level over crest
  n = depends on weir type 1.5 to 2.5





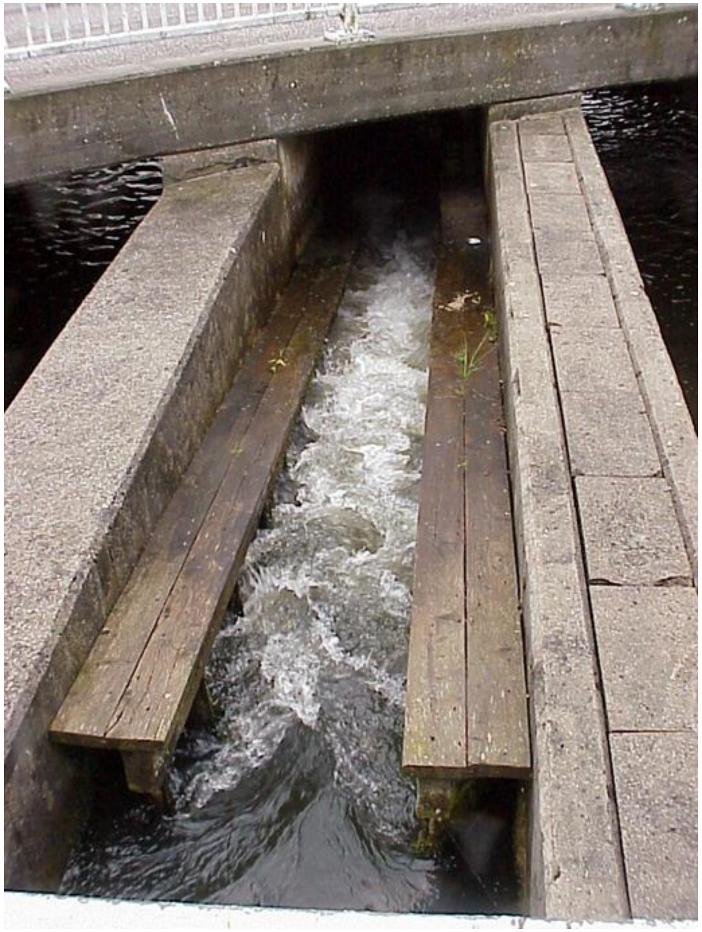
River Engineering

Construction: Weir



River Engineering

Construction: Fish Ladder



River Engineering

Construction: Storm Gate

River Engineering

Construction: Pumpstation

River Engineering

Weir Discharge

- Poleni equation

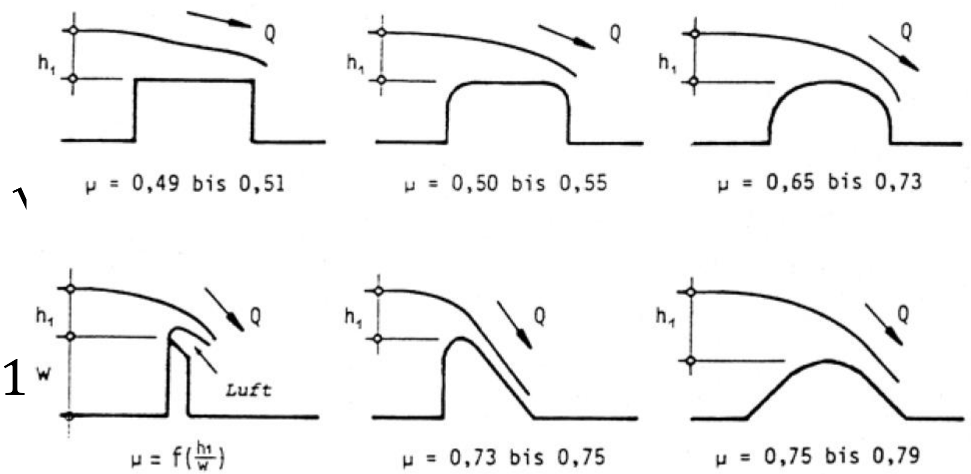
$$Q = \frac{2}{3}\,\mu$$

- sharp weir

$$\mu = 0{,}611$$

laboratory discharge measurement

for $\frac{h_1}{w} < 6$
(water level upstream / crest height)



Parameter μ	
broad, sharp edges, horizontal:	0,49–0,51
broad, rounded edges, horizontal:	0,50–0,55
broad, fully rounded crest:	0,65–0,73
sharp:	~ 0,64
rounded crest, sloped upstream side:	0,73–0,75
root shape, rounded crest:	0,75–0,79

River Engineering

V-Shape Weir for Discharge Measurement

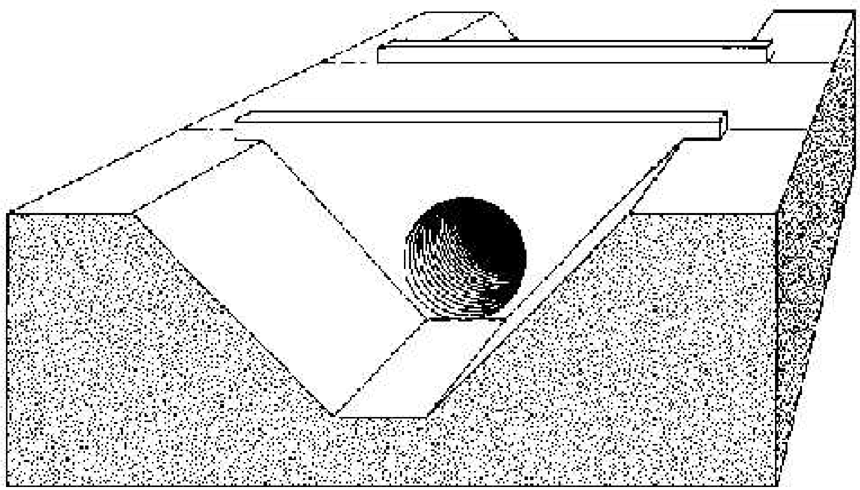
- small discharges (e.g. creeks)
- fixed geometry
- V-shape angle α
- can be combined: e.g. R-Shape
- measured water level h_1
- $Q = \frac{8}{15}\,\mu \tan(\alpha)\,\sqrt{2g}\,\sqrt{{h_1}^5}$
- typical value: μ = 0.58

River Engineering

Construction: Culvert

to manage the flow under a construction (e.g. road)

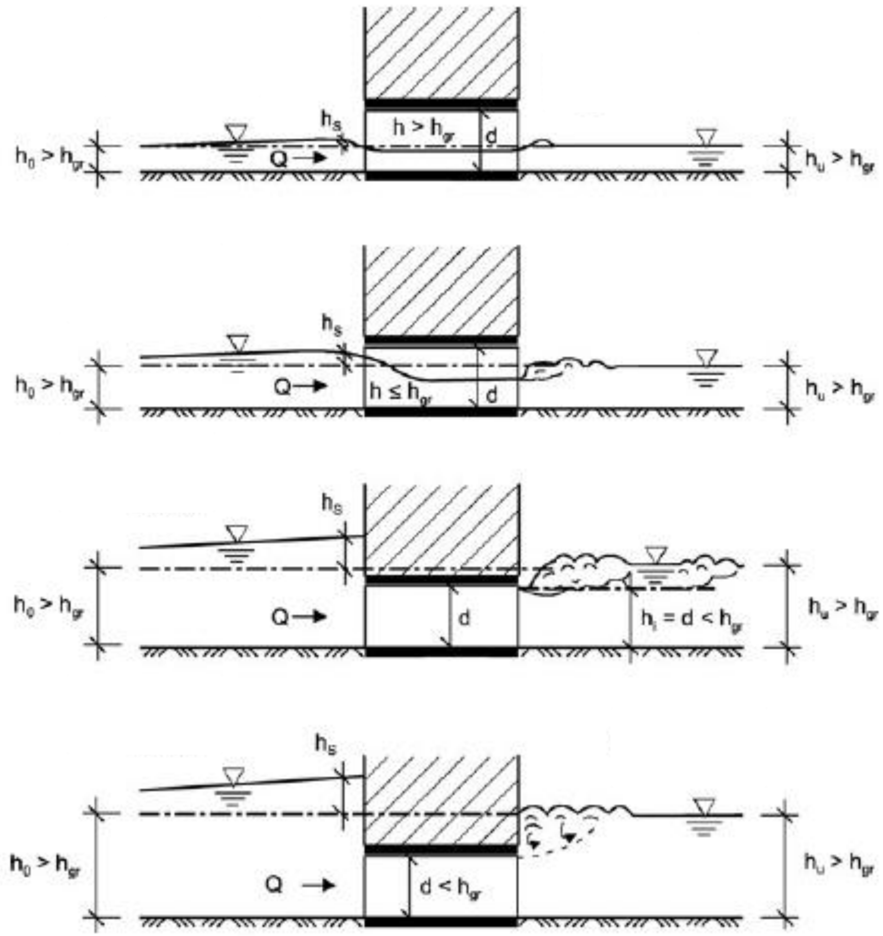
- channel flow <-> pipe flow



River Engineering

Construction: Culvert

- channel flow <-> pipe flow



River Engineering

Construction: Culvert

- Promenade de Paillon in Nice

River Engineering

Construction: Culvert

- Promenade de Paillon

River Engineering

Construction: Culvert

- Promenade de Paillon in Nice

River Engineering

Construction: Culvert

- Promenade de Paillon in Nice

River Modelling

Modelling Approaches

- analytic, empiric model (mathematics)
- physical model (laboratory)
- numerical model (computer)
- AI - artificial intelligent model (computer)

River Modelling

Mathematics: Analytic and Empiric Models

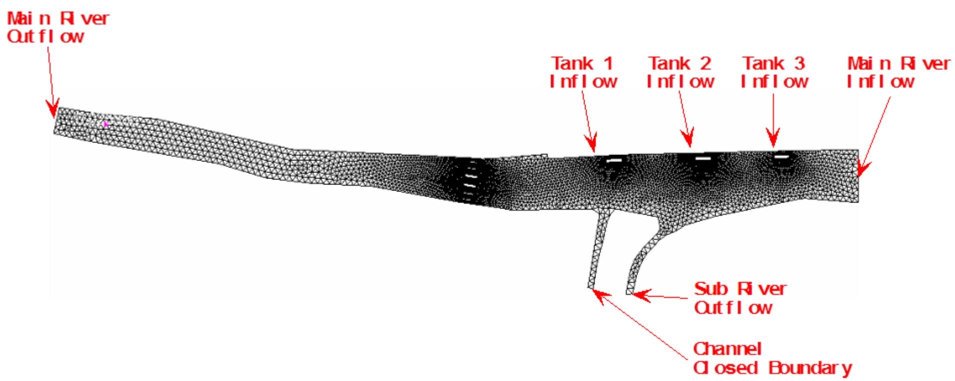
- Weir Equations
- Froude, Reynolds, Prandtl Numbers
- Manning-Strickler Formular
- Navier-Stokes Equation
- Shallow Water Equation
- Saint-Venant Equation

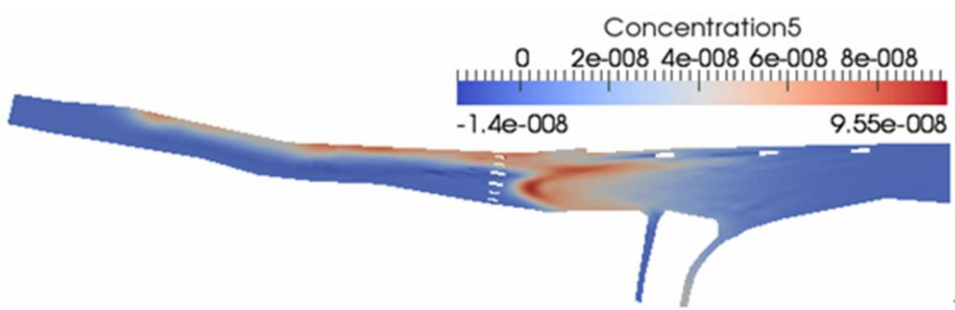
River Modelling

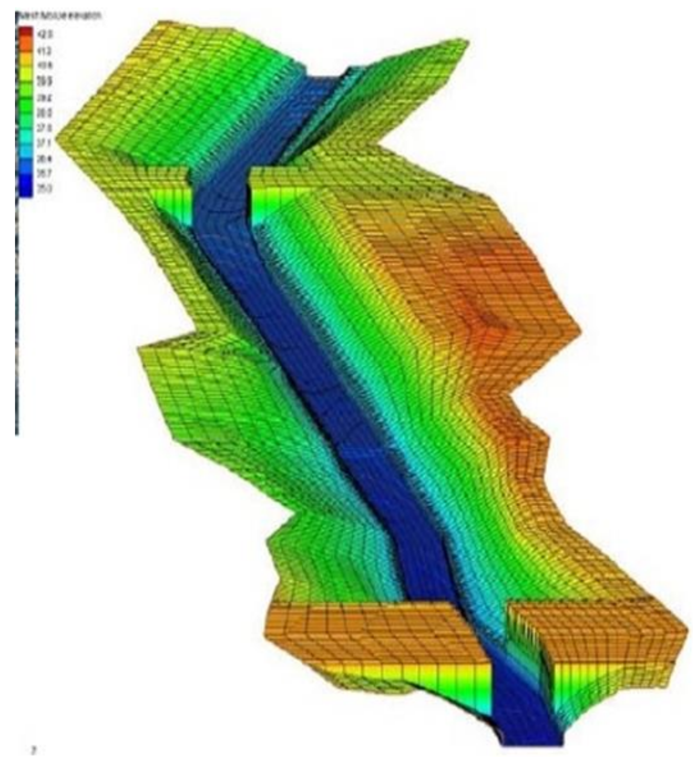
Laboratory: Physical Models

River Modelling

Computer: Numerical Models

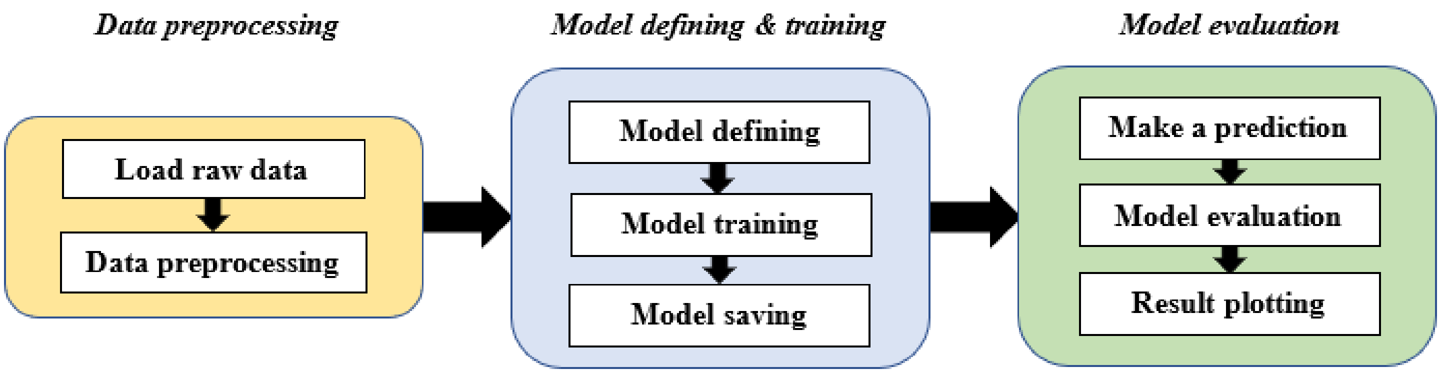


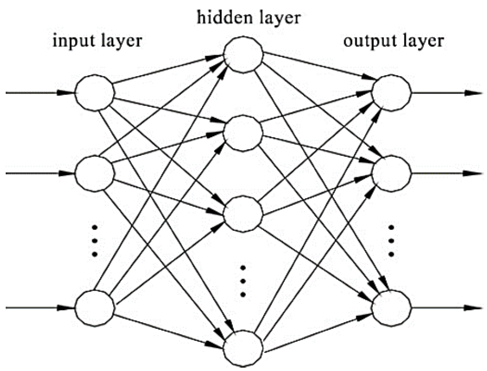


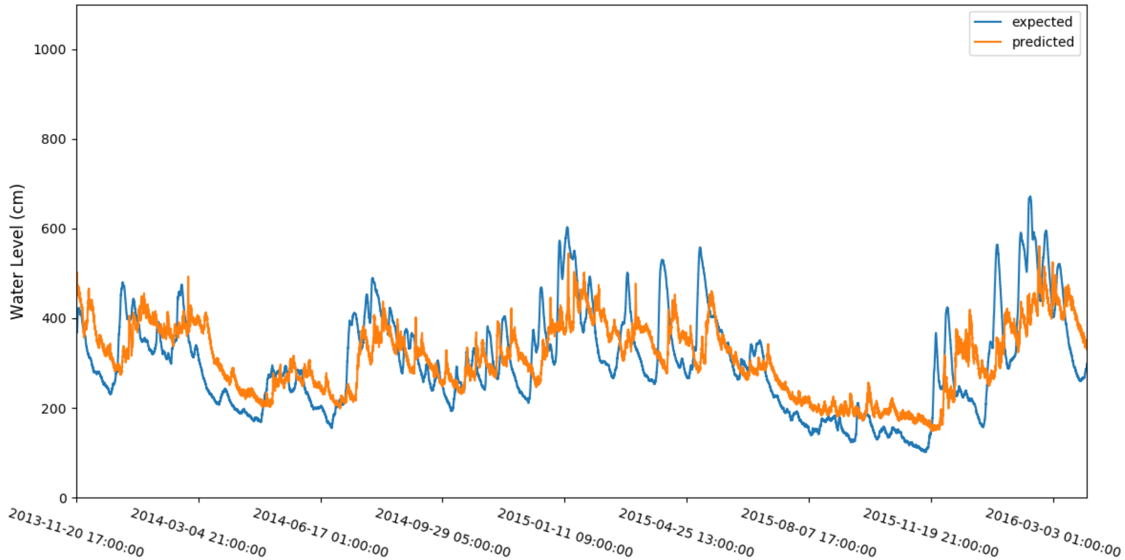


River Modelling

Computer: AI Models – Neural Networks







River Modelling

Computer: Numerical Models

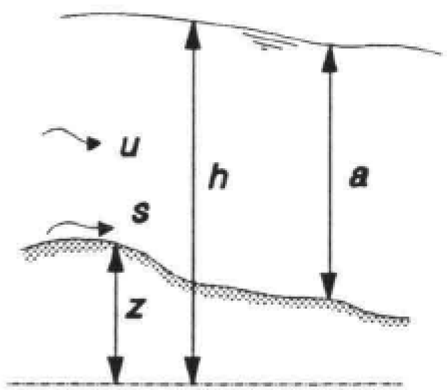
- 1D Model -> 1D in space
- 2D Model -> 2D in space
- 3D Model -> 3D in space

- steady -> time independent 0D in time
- unsteady -> time dependent 1D in time

River Modelling: Hydraulics

Water Flow: Physical State Variables

- water depth -> a
- water level -> h
- bed level -> z
- velocity -> u
- discharge -> q
- sediment -> s



$$h = z + a$$

River Modelling

Input Data

- geometry
- structures
- operational data
- measurement values
- modelling target

River Modelling

Background

- conceptual physical model, assumptions, empiric
- mathematical background
- numerical scheme, properties and parameters
- simulation scenario
- model set-up, calibration and validation
- model result analysis and application

Model Assumptions

1D River Model

- incompressible and homogenous fluid
- flow is mainly one-dimensional
- bottom slope is small
- small longitudinal variation of cross-sectional parameters
- hydrostatic pressure distribution
- …

Mathematical Background

Physical Laws - 1D Saint-Venant Equations

- Continuity Equation (Conservation of Mass)

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_l \qquad q_l = \textit{lateral inflow}$$

- Momentum Equation (Conservation of Momentum)

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q\frac{Q}{A})}{\partial x} + gA\frac{\partial h}{\partial x} + g\frac{Q|Q|}{C^2 R\,A} = 0$$

- two partial differential equations
  two unknowns - two coordinates

Theoretical Background

Numerical Scheme (Abbott-Ionescu, Preismannn, ...)

Continuum Equation

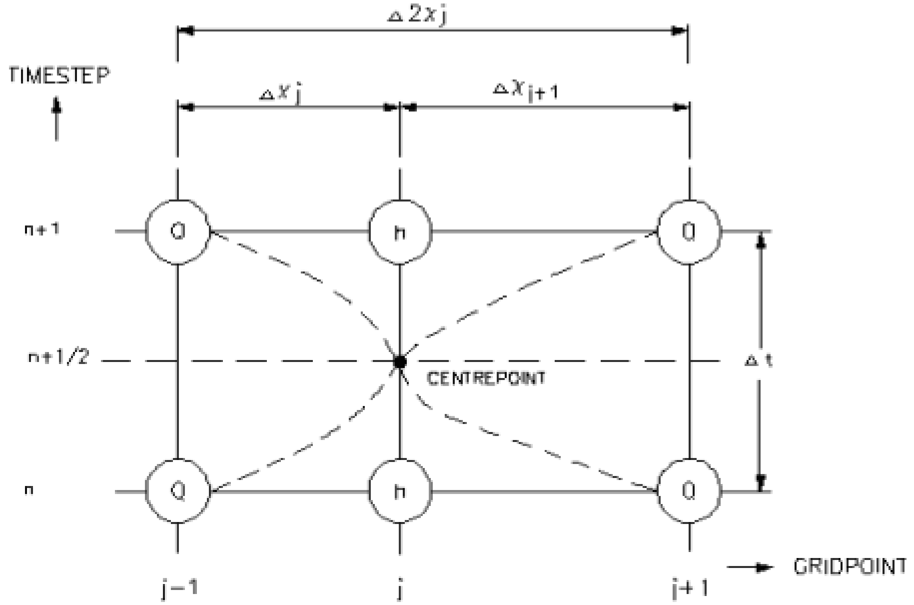
$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad \frac{\partial A}{\partial t} = b_s \frac{\partial h}{\partial t} \qquad \frac{\partial Q}{\partial x} + b_s \frac{\partial h}{\partial t} = q$$

$$\frac{\partial Q}{\partial x} \approx \frac{\frac{(Q_{j+1}^{n+1} + Q_{j+1}^{n})}{2} - \frac{(Q_{j-1}^{n+1} + Q_{j-1}^{n})}{2}}{\Delta 2x_j}$$

$$\frac{\partial h}{\partial t} \approx \frac{(h_j^{n+1} - h_j^{n})}{\Delta t}$$

$$b_s = \frac{A_{o,j} + A_{o,j+1}}{\Delta 2x_j}$$

$$\alpha_j Q_{j-1}^{n+1} + \beta_j h_j^{n+1} + \gamma_j Q_{j+1}^{n+1} = \delta_j$$



Simulation Scenario

Target Definition - Examples

- specific event from the past
- flood situation for a 100 year return period
- engineering activities: dredging, structures, ...
- sediment (, concentration, temperature) transport
- climate change
- water level forecast (navigation)
- ...

Modelling Process

Typical Modelling Steps

- data collection and pre-analysis and -processing
- model set-up
- model calibration
- model validation
- model application
- data post-processing
- ....

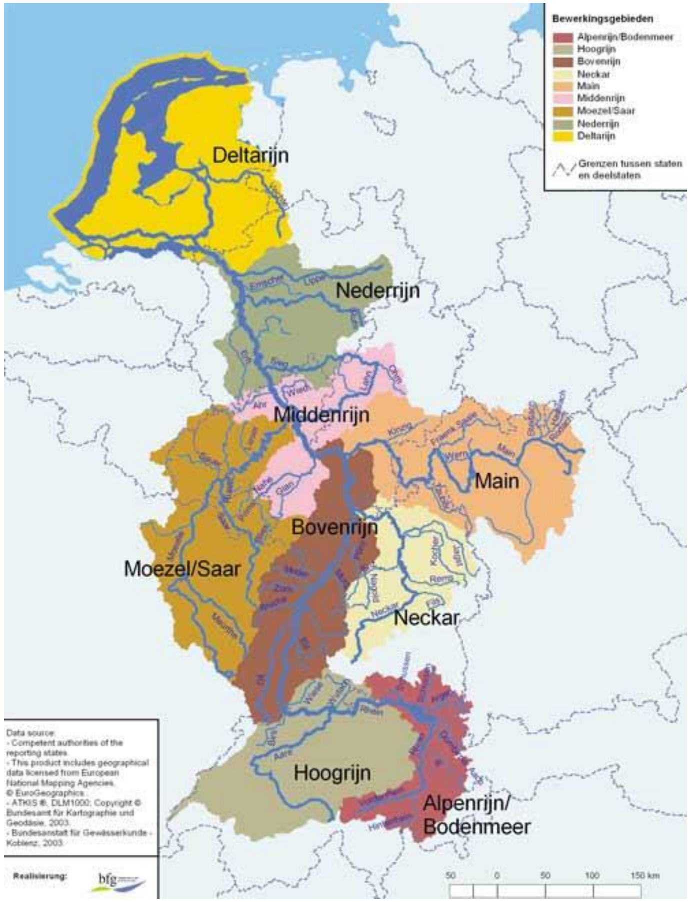
Modelling Results

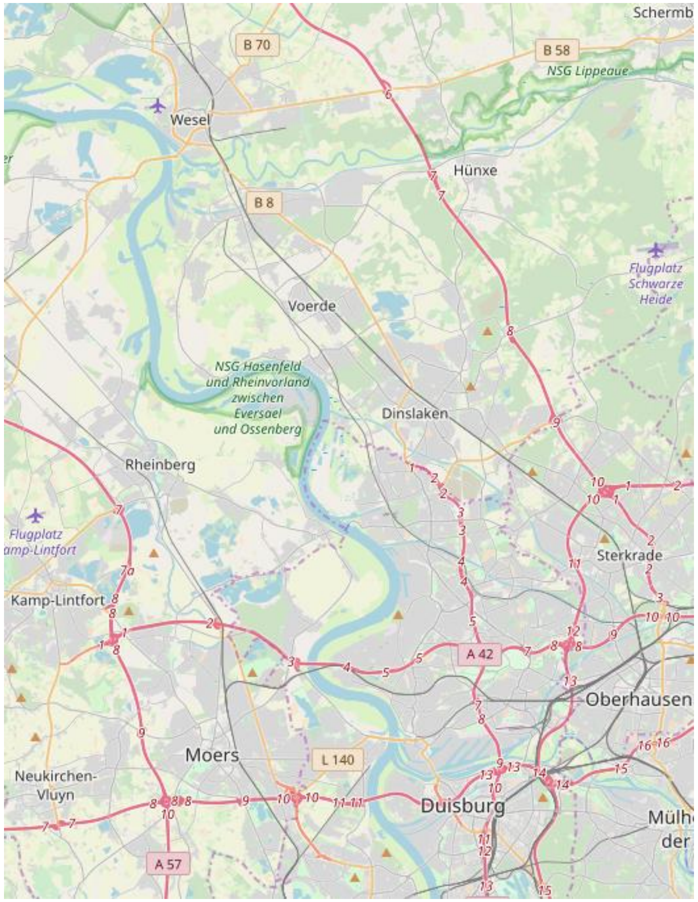
Result Analysis and Application

- identification of key data / information
- sensitivity and uncertainty analysis
- documentation
- presentation
- interfacing
- ….

Application Example

River Rhine – Section Ruhrort - Wesel





reference: bfg, iksr

Application Example

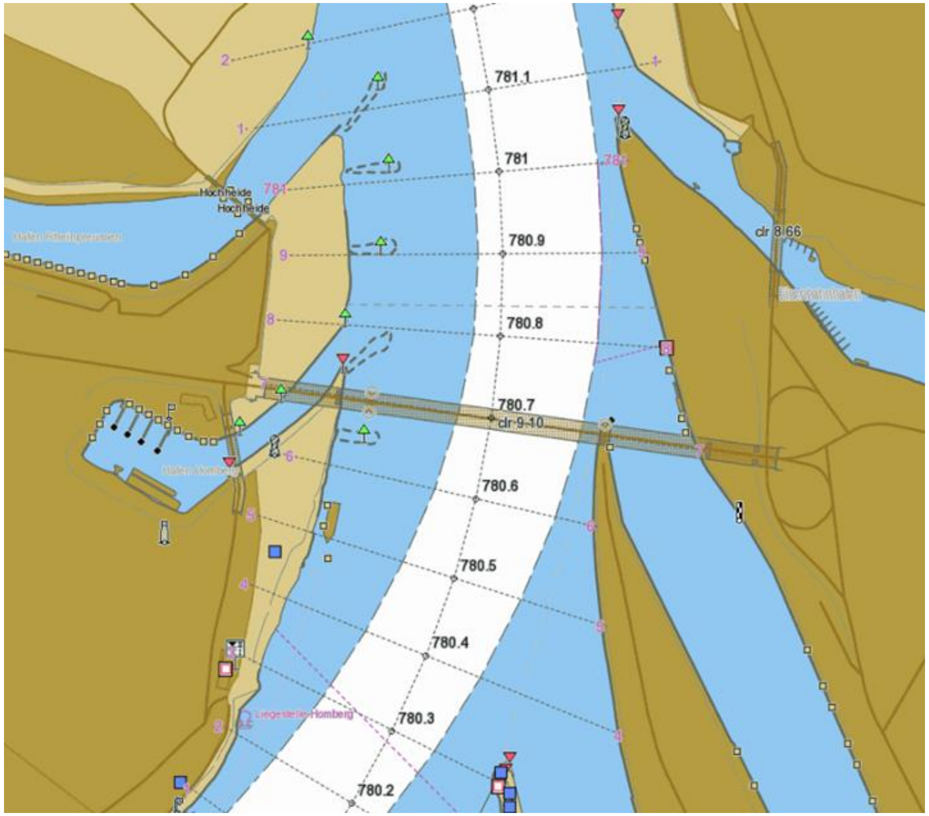
River Rhine – Polder Mehrum

reference: openstreetmap, googlemaps

Application Example

River Rhine – Pegel Duisburg-Ruhrort

https://www.pegelonline.wsv.de/gast/stammdaten?pegelnr=2770010

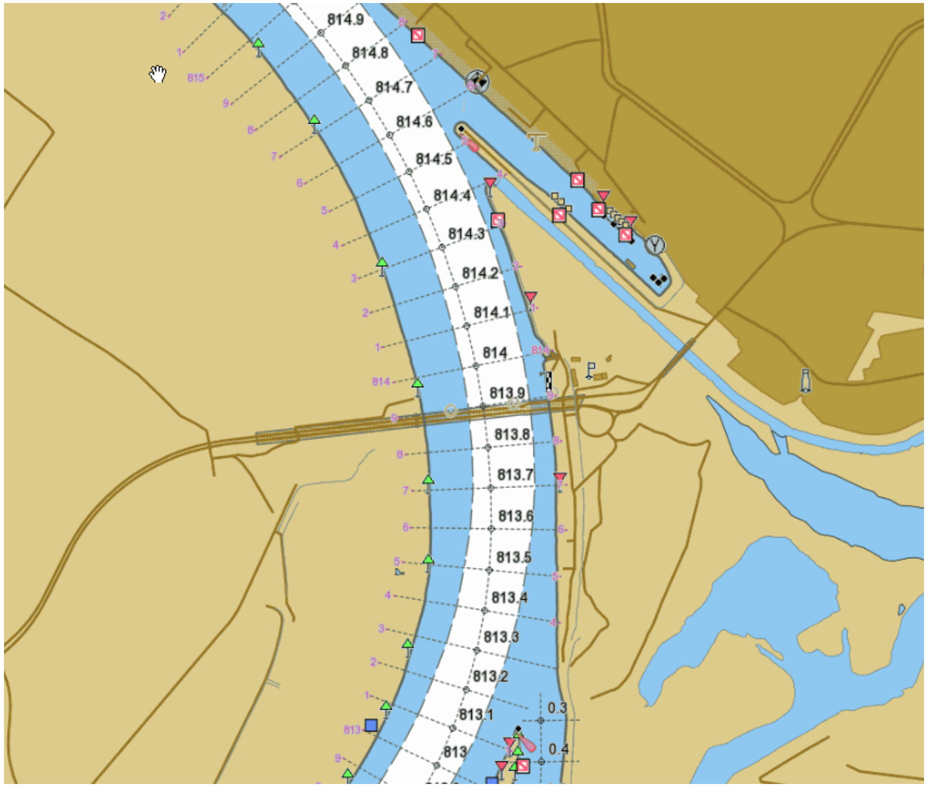


reference: bafg, undine

Application Example

River Rhine – Pegel Wesel

https://www.pegelonline.wsv.de/gast/stammdaten?pegelnr=2770040



reference: wsv

Application Example

River Modelling Targets

- 1D modelling of the river section
- 2D modelling of the river section
- 2D modelling of the polder Mehrum
  for a flood event due to a assumed dam breach

Learning by Doing

Let’s start