Class 2 September 10, 2014

A. Fundamentals in Hydrology
- A.2.The hydrological cycle
- A.3. Physical description of hydrological phenomena
  - A.3.1. Physical quantities
    - -Dimensions
    - -Units
  - A.3.2. Properties of water
    - -Chemical
    - -Physical

Notes

- The Hydrological cycle
  - a) Circulation within the hydrosphere
    - i) Limited to 1 km below the surface (in the lithosphere) to 15km in the atmosphere
  - b) Description of the hydrological cycle can be subdivided into two parts
    - i) Components
      - (1) Storage
        - (a) Liquid, gas, ice, notion of storage
        - (b) Reservoirs <- subsystems (synonymous
      - (2) Transport
        - (a) Circulation
        - (b) Processes
        - (c) Laws describing motion
    - ii) Water distribution
      - (a) Only 3.5% is land water
        - (i) Rivers lakes is a very small fraction of this 3.5% and it is only a bit larger than the biological water (in our bodies)
        - (ii) 69% ice
    - iii) Course pack has a breakdown of the water distribution, and the fluxes (components and transport)
  - c) Notion of residence time
    - i) T_r: average duration for a water molecule to pass through a subsystem (reservoir of the hydrological cycle.
      - (1) T_r = Volume of water stored in reservoir / Flow Rate discharge (km^3 / (km^3/year)) = time as units
      - (2) Example Atmosphere
        - (a) Volume = 12900 km^3
        - (b) Flow Rate = 458, 000 + 119,000 km^3/ year = 577, 000 km^{3-}/year
          - (i) T_r = 12,900 / 577,000 = 0.022 years * 365 = 8.2 days
  - d) A.3 Physical description of hydrological phenomena
    - i) A.3.1 – Physical Quantities
      - (1) Dingman 1984 chap 2+3 fluvial hydrology
      - (2) Physical quantity
        - (a) Value (number)
        - (b) Dimensions (fundamental) rules

(c) Units (cubic)

(3) Dimensions

(a) Rule 1 - Numerical magnitude of a PQ (physical quantity) has no meaning without units of measurement

(i) Units are arbitrary

1. Length for ex; m, ft, cm, mile, furlongs.

(b) Rule 2 – Fundamental dimensions (5x)

(i) Length (L)

(ii) Mass (m)

(iii) Time (T)

(iv) Temperature (θ)

(v) Force (F)

1. Each PQ has a fundamental dimension character except pure numbers (pi – no dimensions)

(c) Rule 3 – Dimensional character of a PQ is expressed as some combination of length, mass (or Force) time, temperature. If else (otherwise) dimensionless. Physical quantity can have either force or mass, not both because F = m*a (newton's second law of motion

(i) The convention is using [ ] square brackets for dimensions

1. Ex; [L], $[L\ T^{-2}] = [L]/[T^{2}]$ =acceleration

2. 2 systems [M, L, T, θ] or [F, L, T, θ]

(d) Rule 4 – PQ expressed [M^a, L^b, T^c θ^d] or [F^d L^f, T^e θ^d]

(i) A,b,c….g ; rational numbers (integers or ratios of integers

(ii) Ex $[M\ L^{-2}\ T^{-1}]$ a = 1 b = 2 , c = 1, d = 0

(iii) F = ma : $[F] = [M]\ [LT^{-2}]$

(iv) Ex; Pressure : $[M\ L^{-1}\ T^{-2}]$ but $[M] = [F] = [LT^{-2}]$ therefore $[M\ L^{-1}\ T^{-2}] = [F\ L^{-2}]$

1. Dimensionless or pure numbers exponents are 0, always [1]

2. Most often M^a or F^e a = e= 1 or 0

3. L^b or L^f -3 <= b or f <= 3

4. T^c and T^g -2 <= c or g <= 2

5. Θ^d -1 <= d <=1

(e) Rule 5 (important) – Dimensions of PQ are subjected to the same math operations as the PQ themselves

(i) Exponentiation

1. $[D^a]^b = [D^{ab}]$

2. $[D^{-2}]^{-0.5} = [D^1] = [D]$

3. $[D^{-2}]^{-1} = [D^2]$

(ii) Multiplication

1. $[D^a]*[D^b] = [D^{a+b}]$

2. $[D^{-2}]*[D] = [D^{-2+1}] = [D^{-1}]$

(f) Rule 6 – Dimensions can be eliminated by multiplication

(i) $[D^{-2}]*[D^2] = [D^0] = [1]$

(g) Rule 7 – Addition and subtraction can take place only with terms of the same dimesions

        (i) Ex; $[D^3]$ + [D3] = wrong
    (h) Rule 8 – All exponents, logarithms, trigonometric functions, are dimensionless numbers
        (i) Ex slope; Tangent = opposite over adjacent
(4) Dimensional analysis of equations
    (a) Rule 9 – an equation that completely and correctly describes a physical relation, has the same dimensions on both sides of the = sign
        (i) If this is the case, it is dimensionally homogeneous
        (ii) If it is not the case, then it is inhomogeneous
    (b) Example of dimensional analysis
    (c) Bernouilli equation
        (i) $H = z + y + V^2/2g$
            1. H = energy per weight of flowing water
            2. z = height above datum [L]
            3. y = flow depth [L]
            4. v = velocity $[L\ T^{-1}]$
            5. g = acceleration due to gravity $[L\ T^{-2}]$
        (ii) H = [L]

Class 3 Sept 15, 2014

Picking up from last lecture

- …Rule 10
    - In an inhomogeneous equation, units for each variable must be specified
    - Except;
        - Exponents, logarithms, trigonometric functions
    - Ex: inhomogeneous equation: Manning's Formula
        - $V = U_m (R^{2/3} S_0^{1/2})/n$
        - U_m - constant
        - R – hydraulic radius ~ flow depth [L]
        - S_0 – bed slope of river [1]
        - n – Manning's roughness factor [1]
        - V – velocity $[LT^{-1}]$
    - Because it is inhomogeneous, the constant U_m must have dimensions, equal to $[L^{1/3}T^{-1}]$
    - Equations are inhomogeneous if the constant has to have dimensions
- Summary on dimensions
    - Fundamental and part of the definition and manipulation of PQ
    - Dimensional manipulations are made on exponents
    - Either have the F or the M system (always convert between the two) (due to F=ma)
        - $[F]= [M][LT^{-2}]$ therefore $[M] = [F] /[LT^{-2}]$
        - Ex; mass density: $\rho = [ML^{-3}]$

A.3.1.2 Units

- Units are Arbitrary
- A few systems
    - International
    - Centimeter gram seconds
    - English
- Table a.3-3 gives you conversion factors
- Conversion of units
    - Converting a quantity of X old units into New units
        - (X old units)* (Y new units)/X old Units) = XY New Units
    - More than one unit, how to deal with it
        - X (OU1/OU2)*(YNU1/OU1)*(1/2(OU2/NU2)) = XY ½ (NU1/NU2)
    - Be careful when the units are squared
        - $X^2 = CF^2 units^2/X^2$
- Example of unit conversion P.18
    - check if homogeneous or not
    - Q=kP – inhomogeneous, the k has to have units
    - See c.p. example

- Recommend using excel for the stuff
- $Q=k_0P_0$
- Verification step
  - Say 3 in/hr 3in/hr ->2.54mm/hr = 76.2 mm/hr
  - Q_o 50*3 = 150 ft^3/ hour
  - Q_n = 0.0557Pn
  - Q_n = 0.0557 *76.2 = 4.25m^3/hr
    - = 0.02832m^3 -> 1 ft^3
- Significant figures; use common sense, not significant figures
  - Use scientific notation
  - Rule of thumb ~ 3 digits are enough
  - Be careful when you are dealing with LOG values – keep many digits and only round at the end.
- A.3.2 Properties of water (digman chap 4)
  - Chemical;
    - Molecular structure
    - Water is very special
  - Physical properties
    - Relationship force -> Motion
      - 2 types
        - Dynamic
          - Either the [M] or the [F] system
        - Kinematic
          - Only [L] or [T]
  - A.3.2.1 Chemical Properties of water
    - 2 important properties of molecule of H_2O
      - Covalent bonds between the hydrogen and the oxygen
        - Very strong bond, hard to separate the atoms
      - Hydrogen bond
        - 2 hydrogens are attached on one side of the molecules, bond angle of 105 degrees, introducing a partial charge at ends, and the partial charges attract their opposite. This polarity is what causes the hydrogen bonding
        - 1/20th of the strength of the covalent bond
        - Important because it explains the special behaviour of water
          - High melting and boiling temperature which is very peculiar given its molecular weight, and how it is an outlier on the trend of weight vs boiling and melting temps
          - 3 states exist in nature
          - Density is lower at crystalline state than at liquid state
            - Hexagonal structure between molecules
            - Density of ice is 0.917 than that of liquid water
              - Important for lakes, among other things

        - 0C hexagonal structure is broken
        - 15C ½ of H bonds will be broken
        - 3.98C is max density
        - 100C h bonds completely broken
        - Important for the lake overturning, and mixing of lake waters, as in the fall the lake water gets to max density at ~4C and it sinks to the bottom, mixing the lake, which is very biologically important
- A.3.2.2 – physical properties
    - Mass Density (ρ) is mass/unit volume = $[ML^{-3}]$
    - 1 gram: mass of $1cm^3$ of pure water at its temperature of max density, 3.98C
    - At 0C table that provides the physical properties of water on pg 23 use ρ = 1000 kg/m^3
        - Except for lake studies and suspended sediment Δ↑ρ
    - Water is incompressible, and is therefore not affected by atmospheric density, unlike for air.
    - Varies with temperature
        - Not a huge variation, but a bit see table pg. 25, and these are relative temperatures
    - Weight density (γ) (gamma)
        - Weight : the force exerted on a mass by a gravitational force
        - γ; $[F]/[L^3] = [FL^{-3}]$ F=ma, γ=ρg
            - typically it is 1000* 9.8 = 9800 N/m^3
            - by gravitational attraction
    - dynamic viscosity (μ) (mu)
        - μ; internal friction of a fluid that resists forces tending to flow
        - very important concept
        - Flume! ☺
        - Experiment (fig. A.3.6)
            - Imagine that there are mini current meters from the bed of the flume to the upper boundary (plate with area A)
            - Upper boundary is mobile
            - Initially it is all at rest
            - Plate is pulled with steady force F (constant velocity)
            - //-->One very important of water – No-Slip Condition
            - Imagine water as // layers of molecules (true only for tiny systems like flumes)
            - Layers in immediate contact with a boundary have the same velocity as the boundary. v_s = same at boundary and at layer in contact
            - v will increase linearly with height<--//
            - difference in the velocity gradient = dv/dy dv= change of velocity, dy = change in height

- plot a graph with velocity gradient on x axis, and the F/A on the y-axis, and you will get a linear line, from 0
- linear regression $y = mx + b$ therefore $y = bx$. Slope of the curve is the dynamic viscosity $\mu == F/a = \mu\ dv/dy$
- F = shear Force F/A = Shear Stress (τ) (tau)

A.3 physical description of hydrological phenomena

A.3.2 properties of water
-Chemical
-Physical
Mass density, weight density, dynamic viscosity, kinematic viscosity, surface tension, capillarity

A.4 Hydrological systems and modelling
A.4.1 System Analysis
A. 4.2 Example of a simple system: the reservoir

- …continuing dynamic viscosity
  - On a graph of F/A (shear Stress (τ)(tau)) on y axis, and dV/dy on x axis, you will get a linear relationship, and the slope of that linear relationship is dynamic viscosity : μ
  - Direct proportional relationship between μ and τ
  - Think of a pack of cards, pulling the top in one direction, and how they follow. Thinking of water as layers of molecules.
  - ONLY APPLIES TO SMALL SCALE
  - Ex: comparing honey and water in a flume,
    - The honey would have a dV_1 (1)/dy(5) much smaller than water dV_2(10)/dy(5)
    - Made up values; velocity gradient
      - honey = 1/5
      - water = 10/5
    - force is constant for both at 10 [F] and A = 5 [L^2]
      - honey: $\mu = (F/A)/(dV_1/dy) = (10/5)/(1/5) = 10$
      - water: $\mu = (F/A)/(dV_2/dy) = (10/5)/(10/5) = 1$
      - $\mu = [FL^{-2}T]$
    - μ inversely proportional to Temperature
    - values are given at zero, and when doing problems, it is expected that you will use a table
    - μ increases with an increase in [C] of suspended solids (rarely used) such as debris flows
    - fluids that have a linear relationship when measuring shear stress vs. dV/dy they are called Newtonian fluids (such as water, Ice however is not)
- Kinematic Viscosity: ν (nu)
  - Ratio of dynamic viscosity to mass density:
    - $\nu \equiv \mu/\rho = [FL^{-2}T]/[ML^{-3}] = [L^2 T^{-1}]$
    - ***Kinematic has no force or mass, while dynamic does***
    - Kinematic viscosity has an inversely proportional relationship to temperature
- Surface tension : (σ) (sigma)
  - Less important but nonetheless still used
  - σ – force tending to decrease with increase in surface are of the liquid divided by distance over which forces act [FL^{-1}]
  - σ- 7.56×10^{-2}N/m
- Capillarity
  - Important: Pores in soil
  - Meniscus- attraction and repulsion in a container

        - Θ – contact angle (between container and water) < 90 == attraction
    - Capillary rise: h
        - Attraction of molecules of water between themselves and between the molecules and the container
        - H = (2 σ cos θ)/ (γ R)
            - R – Radius
            - γ – weight density
            - Θ – contact angel
            - σ - surface tension
        - Movement of water in
            - porous media (soil)
            - trees
        - dc = Critical diameter to determine dominating force
            - capillarity (small diameter)
            - gravity (large diameter)

- A-4 : Hydrological systems and modelling
    - Hydrology is so complex, so we divide into something less complex
        - Incomplete understanding of all the processes
        - Many interrelationships (see C.P.)
- A.4.1 – System analysis
    - Use the concept of a control volume (3D reference system)
    - Example: Fluid transport
        - How does fluid flow through a control volume? (soil, river,)
        - Input (I(t)) → VOLUME (F transfer function) → Q(t) output
        - Restrictions:
            - temporal scale
            - spatial scale
            - number and the detail of the interactions
                - (drop the big and small, and just left with the main focus, as it is impossible to model for everything)
        - Control volume allows application of physical laws
        - All models based on 2 fundamental principles
            - Mass conservation (mass can neither be created nor destroyed)
                - Continuity equation
                    - dS_{torage}/dt = Input- Output (balance0
                - if Input = output then dS/dt is 0
            - a) Momentum: based on newton's second law F= ma
                - If you apply a force, the object will move in the direction that the force is applied and move proportionally to the force applied
                - Used for short temporal scales (hours-days)
            - b) energy: 1^{st} law of thermodynamics
                - longer temporal scales (months, years)
        - Predictions – function of boundary conditions in volume, and initial conditions
- A.4.2 Example of a simple model: the Reservoir

- Start simple – add complexity
- Applications: lake
  - I → Δh – difference in storage → Q
  - Objective: predict h (storage volume)
  - Tube I same size of Tube 0
  - Q = V A but if same size input ant output Q = V and drop the Area
- 1 – $h(t) = k*v_o(t)$ – Momentum equation
  - $v_o(t) = h(t)/k$ (t=time)
- 2 – $h(t) - h(t-1) = I(t) - O(t) = v_i(t) - v_o(t-1)$ – Continuity equation
  - $v_i(t)$ – Boundary condition
  - $h(t-1)$ – initial condition (t==0)
  - $h(t) - h(t-1) = v_i(t) - h(t)/k$
  - factorization
    - $h(t) - h(t-1)/k = v_i(t) - h(t)$
    - $h(t)*(1+1/k) = v_i(t) - h(t)$
    - $h(t) = (v_1(t) + h(t-1))/ (1+1/k)$

A Fundamentals in Hydrology
A.4 Hydrological systems and modelling
    A.4.1 System Analysis
    A.4.2 Example of a simple system: the reservoir
    A.4.3 Classification of hydrological models
    Slides physical modelling
B Water in the watershed
    Introduction
    B.1 Organization within the watershed

- Recap from Monday
  - $H(t) = 10\ v_o(t)$
  - 10 is a constant k
  - Initial conditions $h_o = 10$
  - Boundary conditions $v_i(t) = 1$

T	V_i	H	V_o (h(t)/k)
0	1	10	-
1	1	10	1 (INPUT = OUTPUT)
2	1	10	1
13	1	10	1

  - If input == output
    - Is steady state equilibrium
- EX2
  - $V_i = 2$
  - H(2) = (2 + 10.91/1+(1/10))

T	V_i	H	V_o (h(t)/k)
0	2	10	-
1	2	10.91	1.09
2	2	11.74	1.17
13	2		

  - Converges at h(t)=20
- EX 3
  - Variable $v_i(t)$
    - $v_i(t)$ = 0.5^t while t>=1
    - $v_i(t)$ = 0 while t>=6

T	V_i	H	V_o (h(t)/k)
0	-	10	-
1	0.5	7	3.5
2	0.25	4.83	
13	0.125		

  - h(1) = (0.5 + 10)/(1+ ½) …etc.

  - When will it be empty? It depends on precision- you have to choose a threshold for precision
  - Input == output ➔ equilibrium
- Example : managing a lake controlled by a dam
- A.4.3 Classification of hydrological models
  - 1)Physical Models
    - Scale models (everything is divided by a scaling factor (ex, 1/20th of nature)
      - Dimensions of watershed/hill slope/river scaled down/ sediments too!
      - Ex Sunwapta (Alberta) field prototype is the term
    - Analogue models
      - Similar to field prototype, but not scaled down precisely
        - Ex confluence, hill slope
    - Why physical models?
      - Lack of understanding of how everything works, too complicated to be able to simulate in a numerical model
  - 2) Abstract models
    - Works well for systems conceptually well understood
      - Explain 5 sources of variation
        - Time
        - Space (3D)
        - Randomness
      - Have to account for probability (stochastic models)
      - If else it is deterministic, like the reservoir model
      - Figure A4-3 all models can be classified in this model
  - Sunwapta river (Alberta)
    - Field prototype using measurements of real nature to make lab models
    - Creating a laboratory flume (model grain size had to be really precise, as scaling of silt is difficult)
    - Flume confluence (Leeds)
      - Analogue model – not representing a field model
      - Laser Doppler anemometer – super precise measurements that can't done in the field
      - River confluence, different bed height, or different angles
    - Abstract field model
      - Nicolet river example
      - All three have merits, and can be combined to really understand what is going on

Class 7 Sept 29, 2014

Informal Evaluation
B Water in the watershed
Introduction
B.1 Organization within the watershed
  B.1.1 Cartographic representation of Watershed
  B.1.2 Hierarchy of streams: stream order
  B.1.3 Drainage areas
Assignment #2

B – Water in the watershed

- Introduction
  - What is a watershed? – an area that drains to one point
  - Fundamental system (for hydrology) organized by the transport of water to the stream
  - Recursive entity (imbricated at various scales (like Russian dolls, small watersheds within larger watershed, which is part of another watershed))
  - Topography (elevation) that will determine the boundaries (the topographic divide)
  - Watershed is a unit of analysis with "clearly" defined boundaries
      - The water may infiltrate, (pheatric divide: underground divide) making it less clear
  - Watershed comprises of
    - Topographic divide
    - Hill slopes (from the topographic divide to the streams/rivers)
    - Streams (organized in networks)
  - Watershed should be seen as a system of transport of water and sediments
- B.1 Organization within the watershed
- B.1.1 cartographic representation of watershed
  - Hydrographic network = f
  - (scale of map, method of cartography, source info(aerial photos, DEMs)
    - A change in scale will influence the way that you represent the watershed
    - Source of Information
      - Can influence the boundaries and how detailed they are
      - Geobase.ca, not same resolution within the same country,
    - Be cautious and be aware that cartography will affect watershed
- B.1.2 Hierarchy of streams: stream Order (used in ecology – very broadly used)
  - Any hydrographic network has to be ordered, = organized structure, comparable to trees
  - River segments connected by junctions/tributaries/confluences
    - 2 types
      - External (E); sources
      - Internal (I); bounded by 2 junctions
        - Trellised are controlled by synclines, differential rates of erosion
        - Rectangular are controlled by faults
        - Deranged is created by glaciation
    - Order in networks

- 2 methods;
  - Horton Strahler order (often just Strahler)
    - 2 of the same order have to join in order to go up an order
    - The junction of two numbers that are not the same will not result in a change of order, the highest order will preside.
  - Magnitude (Shreve)
    - Each junction will result in an increase in the magnitude, simply add the number of tributaries into the river
- Laws of stream order

Order (u)	# of segments (Nu)	Bifurcation ratio (R_b)
1	10	3.33 3.00
2	3	
3	1	

- Bifurcation ration R_b the ratios are always very close to each other
- $N_u/N_u+1 = R_b$
  - Number of segments of order u / number of segments of order u+1
  - $N_u = R_b^{k-u}$ k = highest stream order this works fairly well in predicting the number of segments
  - R_b average is (sum of R_bU/ order)
- Exponential regression $y= ab^x$ ///a = y-intercept, b^x = slope
  - (Linear regression y = a+bx)
  - Method to plot the number of segments, in order to get a straight line
  - If graphed on a linear graph, you will get a curve
  - Log on the y axis transformation will give you a straight line, which allows you to do a regression
  - The slope of the regression is the R_b
  - Because the y-axis is transformed into log, we must use the log inverse 10^, to find R_b
  - Because the slope is negative (k-u), we must use $R_b = 10^{-\text{ slope of the regression line}}$
- Horton – Strahler Laws of drainage composition
  - (Not just for stream numbers (R_b))
  - Relationship between order and
    - # of segments inversely proportional to stream order
      - Verify $N_u = R_b^{k-u}$ what do you observe on map
    - Average length of segments is proportional to the stream order
      - Law of stream length
    - Drainage area is proportional to stream order
      - Law of drainage area
    - Slope of the river channel is inversely proportional to the stream order
  - There is a relationship between the bifurcation ration and the discharge rate, much faster/intense peak flow on low bifurcation ration while a

high bifurcation ration will have a delayed peak flow that is less intense and longer lasting

- Laws are also used in biology
  - Ex; blood network R_b = ~3.2
  - Bronchi R_b = 2.4-2.8
- Lot of regularity out there for the R_b
  - R_b is normally 3.5
  - R_L =1.5-3
  - R_A = 3-6
  - Why?
    - Order in nature, or problem with notion of order, and that it is quite rigid, and takes a lot to change it, hence there is not a wide range
      - Problem with cartography too, way that you represent the watershed
    - Alternative methods were sought to represent watersheds – shrives magnitude
    - Stochasticity (randomness)
    - Came out of dissatisfaction with the stream order method, where everything is too ordered.

Class 8 Oct 1, 2014

Informal evaluation results

B.1 Organization within a watershed

B.1.3 Drainage areas

Slides stream order and drainage density

B.1.4 Evolution of drainage basins

B.2 Precipitation over a watershed

B.2.1 Terminal velocity of a drop of water

- Monday mid-term format (15^{th} of Oct)
- B1.3 Drainage Areas
    - Stream order laws;
        - Links between # of segments and river length
        - Links between # of segments and area
        - Hack 1957 : relationship between length and area of a watershed
            - Power function : $y = a x^b$ ($\log_x$-$\log_y$)
            - $L= k A^b$ // $[L] = [L^2]$ // b should be 0.5 to be homogenous, however hack found b == 0.6 from empirical observations
            - If you are changing scale, and b==0.5, the shape will not change, proportional reduction, enlargement
            - however since b==0.6 the shape changes when enlarging, becoming more elongated (Allometry is what this is called (change in shape when the scale changes))
    - drainage density varies, if relief constant
    - if drainage density constant, relief varies
        - young landscape has a very up down relief, old landscape has a relatively flat landscape
    - Drainage density (Dd) linked to F. $F == 0.694\ Dd^2$ (drainage density is only calculated at the surface)
    - Controlling factors for Dd
        - Watershed characteristics
            - Amount of runoff, vegetation (affects infiltration), slope, climate, geology. Most are interrelated
        - Time, geological time scape, will flatten mountains
        - Human interventions: particularly in agricultural watersheds
            - Drainage networks are often doubled for agriculture, as well as meanderings are straightened
- B.1.4 Evolution of networks with time
    - Since the 18^{th} century this has been a question
    - A lot of indirect observations because it is not visible.
    - Also there is laboratory modelling to predict/gain knowledge about it
    - Lab Methods
        - Substitute space/time, represent in hours what would take 1000s of years. Can also control the slope

        - Headward erosion: the upstream area grows towards its source, as it erodes and carries sediment downstream. Quicker if the slope is higher.
    - Numerical modelling
        - Headward erosion causes the watershed to grow, opposite direction from stream drainage
    - High drainage density
        - A very large amount of little tributaries,
    - Medium
        - Big channel, many tributaries
    - Low Drainage density
        - One big channel, few tributaries
- B.2 Precipitation over a watershed
    - Big problem for hydrologists (Pb = problem)
        - Spatial & temporal variability in precipitation
        - Variability (Δ) of quantity of water over a watershed
    - Weather stations - point measurements
        - Estimation of volumes,
        - Point measurements are widely spaced in rural areas
    - Climatology; not in detail but very important in hydrology
    - One important point: velocity of a drop of water:
        - The impact of the drop of water will detach particles, leading to transport of sediments. The force of the drop falling will dislodge sediment
- B.2.1 Terminal Velocity of a drop of water.
    - Force pulling drop down: gravity// function of weight
    - Forcing pushing back up
        - Friction (drag) function of the area of the drop
        - Buoyancy, the force of the fluid it is moving into // function of weight and surrounding air (fluid)
    - Gravity $Fg = \rho_w*g*Vol$
        - $g=9.8m/s^2$
        - $Fg = \gamma_w *Vol$ // $[F L^{-3}] [L^3]$
        - Volume = $(pi/6) D^3$
    - $Fb = \rho_a*g*Vol$
        - ρ_a = air mass density
    - $Fd= Cd*\rho_a* A*V^2/2 = [F]$
        - Cd : drag coefficient [1]
        - ρ_a air density $[M L^{-3}]$
        - A = cross sectional area of a drop $[L^2]$ $piR^2 = pi (D/2)^2 = (pi/4) D^2$
        - V = velocity $[L T^{-1}]$
    - Terminal velocity
        - Force balance; downward forces = upward forces
        - Fg = Fb + Fd
        - $\rho_w*g*Vol = \rho_a*g*Vol + Cd*\rho_a* A*V^2/2$
        - want to isolate the velocity

    - $V = \{(((4/3)*D*g) / Cd) * ((\rho_w / \rho_a) - 1)\}^{1/2}$
  - Terminal velocity is about 32km/hr maximum – imagine what that does to sediments!
  - Link between total volume and the spread of drop sizes

Class 9 Oct 6, 2014

Format of the mid-term exam

B water in the watershed

- B.2 Precipitation over a watershed
  - B.2.1 Terminal velocity of a drop of water
  - B.2.2 Temporal/spatial variability of precipitation
  - B.2.3 Methods of estimation of volumes of precipitation
  - B.2.4 Role of vegetation on spatial and temporal distribution of precipitation

- B.2.2 Temporal and spatial variability of precipitation
  - Structure of precipitation
    - Micro-scale: convection cells which last ½ hour
      - Highly variable in intensity
      - Growth-> maturity-> disappears
      - Very common, not that interesting for hydrology
    - Meso-scale (medium)
      - Small (150-400km^2) to large (2300 – 4700km^2)
      - Mixture of developing cells, thunderstorms, showers
      - Intensity overall is medium, can have periods of high intensity, but overall medium
    - Synoptical
      - Mixture of meso-scale structures, over 10,000 km^2
      - Tropical storms, fronts, hurricane
      - High intensity in general
  - Temporal variability of precipitation
    - Intensity == $\frac{\text{height of water at 1 point}}{time\ interval}$
    - Mean/max intensity
    - Hyetograph (huetos == Greek for rain) graphs that show rainfall/time in minutes
      - Incremental = rainfall depth as a function of time (bar)
      - Cumulative = sum of increments through time (line)
      - Slope of graph == intensity
      - Graphs can have a variable timescale from 1hr to 5 minutes, normally 1 hr

        - Comparison of precipitation
            - Mean intensity (i)
            - Max intensity (for a given interval)
            - Duration (d)
            - Total precipitation = i*d
            - Maximum intensity will always be high over a short period of time and decrease over longer time periods
        - Can do probability of precipitation graphs
        - Probability / time of day
    - Spatial variability
        - Relationships between climate and orography
            - Global controlling factors
        - Hard to get accurate readings, as the relationship between density of weather stations is not consistent, not much data for remote areas
        - Always have the problem that you have few point data (weather stations) and have to cover aerial data-> interpolate the point data to describe an area
- B.2.3 Methods of estimation of volumes of precipitation
    - Point-> space -> volume
    - 3 methods
        - Arithmetic mean
            - Mean precipitation (P with dash on top)
            - (Pj – precipitation at a water station j)
            - N = number of measuring points
            - P = sum(Pj)/ n
            - Only for points within a watershed
            - Volume = P(mm) * area of watershed(km), be careful with units as you will have to go from mm->km or reverse
            - However can lend itself to bias over a large areas with poor distribution of measuring stations
        - Thiessen polygons (Voronoi, Drichlet)
            - Idea is to solve uneven distribution of weather station distribution and uneven distribution of precipitation.
            - If area of P1 >> the weight of p1 will also be >>
            - Volume = ∑Pj*Aj
                - A = area
                - J = station
                - P= precipitation
                - N = number of stations
            - How do you get the thiessen?
                - Connect points in triangles
                    - Delaunay triangles
                - Mid-distance of triangle sides
                    - Draw a 90 degree line from the mid points of triangles, should all connect, indicating the area of influence

- Isohyeta method
  - Interpolation between weather stations
  - Determine optimal interval between isohyets
  - F(range of values) = max – min
  - Optimal number of isohyets is 5-6 (27-14 = 13)
  - Say for 5 isohyets
    - Interval = range/3 of isohyets = 13mm/5 = 2.6 but round number to 3
    - Position isohyets
      - 14,17,20,23,26
      - then draw them like you would isolines in mapping
      - find the midpoint and estimate the average of amount of rain per area

Class 10 Oct 8, 2014

B Water in the watershed
B.2 Precipitation over a watershed
- B.2.1 Terminal Velocity of a drop of water
- B.2.2 Temporal/spatial variability of precipitation
- B.2.3 methods of estimation of volumes of precipitation
- B.2.4 Role of vegetation on spatial and temporal distribution of precipitation

B.3 Runoff: types and controlling factors
- B.3.1 Infiltration
- Video on infiltration

- B.2.4 ROLE OF VEGETATION ON SPATIAL AND TEMPORAL DISTRIBUTION OF PRECIPITATION
  - Evaporative losses in temperate climate
    - 10-25% /year deciduous trees
    - 20-45% /year for conifers
      - Not negligible values, so you have to take them into account
  - Throughfall: rain that will hit the ground
  - Stem-flow flow along the trees: 0.6-15% of rainfall, species dependent
  - Interception is 12-50% under temperate climates
    - When assessing underground moisture, it will vary beneath the tree, vs between trees, it gets increasingly more complex when you increase the resolution of your scale. Whole field about forest hydrology

- B.3: Runoff: types and controlling factors
  - How does water travel towards the streams?
  - What are the preferred routes?
  - Key is infiltration:
    - Surface runoff: rapid runoff
    - Subsurface: slow runoff
    - A lot of variability in time/space of infiltration
      - Δ in volume
      - Δ in response time
      - Δ in peak (max)
- B.3.1 – Infiltration
  - Process by which water moves from the surface to the interior of a porous media, like soil
  - Defining porosity : (eta) η is the volume of pores / total volume == Percent
    - Primary: grain, ~30-40%
    - Secondary: cracks, fractures, joints
  - Water content: θ (theta)
    - Θ volume of water / total volume
    - $0 < \theta <$ porosity (η)
  - Saturation:
    - point where all the pores are filled with water θ == η
  - Hydraulic conductivity
    - K – capacity of a porous media to transmit water $[LT^{-1}]$

- 3 zones during the process of infiltration
  - Saturation zone,
  - Transmission zone
  - Wetting zone
- Link between texture porosity-conductivity-infiltration
  - Very complex
  - It is a function of 3 components
    - Water input in soil
    - Water storage (function of storage)
    - Transmission
      - Function of 2 forces
        - Gravity, (water moves downward)
        - Capillarity: vertical but mainly lateral under tension
          - Capillarity force inversely proportional to diameter, small diameters result in capillarity force dominating
      - K = γ (weight density) D^2 / 32 μ (dynamic viscosity)
        - Works out to $[LT^{-1}]$
- Porosity doesn't vary that much, but hydraulic conductivity does vary quite a lot!
- Pores exert a tension (negative pressure)
  - If you look at water content and water tension, (θ vs ψ) water tension will decrease when water content diminishes, (infiltration)
  - However when you reverse, (exfiltration) it spikes up and then levels off
    - Graph type is hysteresis (graph that have a different pattern for way down than way up)
  - During wetting: small pores will fill first
  - When drying: large pores will empty first
  - Way more tension when there is a little more water compared to when there is a lot of water
- Looking at exfiltration
  - At 0 there is saturation, and it goes down from there, not linearly
- Very dynamic environment however
  - Affects the water table
- Hydrological classification of soil
  - Forest floor
  - Root zone
  - Intermediate/ variable zone
  - Zone of saturation
- Water table and river height very much linked
- Hydraulic conductivity varies with relative saturation,
  - A lot of tension will make it very slow, from 0-80% saturated, it is rather slow, because of cohesive tension, but above 80% it rises dramatically.
- Infiltration rate (f) $[LT^{-1}]$
  - Rate of penetration of water in a porous media/soil

- Infiltration capacity
    - maximum infiltration rate of a soil for given conditions

- combining runoff and precipitation:
    - if the intensity of precipitation (i) exceeds > capacity,
        - then f == capacity of the material //fig a in b.3.10
    - if rain intensity (i) < capacity
        - then f == i rate of precipitation // fig b in b.3.10

// excess precipitation which doesn't infiltrate, fill depressions or runoff

- f will decrease rapidly at the beginning of precipitation, then slows, then reaches a constant level, there is a curve that looks like that – downwards exponential towards asymptote (constant level)

B.3.2 Estimation of the rate of infiltration

- Laboratory measurements
- Estimate from the hydrological balance of a surface (know input, and output, and the difference must be the infiltration)
  - Usually done with descriptive/empirical models (they have aspects that conform to the watershed you are studying)
  - Ex. Horton (1933)
    - Model of decrease of f (f==infiltration rate) with time.
    - $f(t) = f_c + (f_0 - f_c)e^{-kt}$
      - t = time
      - f_0 initial infiltration rate $[LT^{-1}]$
      - f_c final infiltration capacity $[LT^{-1}]$
      - k = decay constant
    - variable for variable Canadian soils
    - ex.
      - t=0
      - f_0 16 mm/hr
      - fc 5mm/hr
      - k = 2.8
    - $f(0) = 5 + (16-5)\, e^{-2.8*0}$
      - = 5 + (11) *1
      - = 16
    - Ex2.
      - t= 40 minutes = 0.667
      - f_0 16 mm/hr
      - fc 5mm/hr
      - k = 2.8
    - $f(0) = 5 + (16-5)\, e^{-2.8*0.667}$
      - = 5 + (11) *0.1454
      - =
    - Cumulative Form = F(t)
      - F(t) = integral of: f(t)d(t)
      - Tells you the height of infiltrated water during a period of time from 0 to time t
        - $[LT^{-1}]*[T] = [L]$
  - Philip model: "physical" model
    - $F(t) = \frac{1}{2} St^{-1/2} + K$
      - S = soil suction - capillarity
      - K – hydraulic conductivity - gravity
      - As time carries on, the capillarity rate will eventually go to 0 going towards hydraulic conductivity, as time progresses.
    - More used for the cumulative form than the other one
      - $F(t) = St^{1/2} + Kt$
    - Better to understand than Horton, as it uses capillarity and gravity, and not a decay constant

- Green – Ampt method
  - L = depth to wetting front
  - h_0 = depth of surface retention
  - θ_i = original water content
  - η = Porosity
  - ψ wetting front soil suction head (cm)
  - equation given for cumulative form
    - numerical iteration is needed to solve the equation
  - The error range for each variable in the equation can be, and often is, very wide.
- Factors controlling infiltration rate curve
  - Infiltration rate curve is a function of 3 main parameters
    - Characteristic of precipitation
      - Intense/long will have the most dramatic impact,
        - Particle compaction
        - Swelling of clays – less infiltration space
        - Surface sealing (connected to swelling of clays)
    - Soil properties
      - Texture + structure
        - Coarse vs. fine = determines the size of the pores
        - Presence of organic material
      - Depth of soil +Distribution of humidity
        - Depth influences volume of water that can infiltrate
      - Thick soil, coarse material, lots of organic material == high infiltration rate
      - Shallow, clay soil == smallest infiltration rate - most damage done.
    - Vegetation and land use component, can really impact the infiltration rate curve
      - Vegetation + litter: protection against impact of drops
      - More fauna & Flora => more macro-pores
      - Change land use -> drastic change in infiltration
        - Forest vs. asphalt

B.3.3 – Types of Runoff

- Hortonian runoff – excess precipitation
  - Precipitation> f(t) =>excess
- Saturated overland flow
  - Direct precipitation over saturated areas
- Through Flow (subsurface flow)
  - Through a porous media, movement sometimes through translation
  - Macro-pores
- Resurgence (Return flow)
  - Starts as sub-surface => ends at the surface
- Base flow / groundwater flow
  - Much longer residence time
- Between the rain and the discharge, a lot can happen, it is the job of the hydrologist to work on this

B.3.3.1

- Hortonian Runoff
  - Concept is that there is rain – infiltration = excess precipitation (runoff)
  - Storage in depressions: function of the roughness of the surface
    - Roughness defined by;
      - Topography
      - Presence of aggregates
      - Organic matter
      - Ploughing, compaction due to machinery
    - Difficult to overlay an incremental hyetograph on a Horton model graph
  - Problem is that Horton's model starts at t=0, but rainfall doesn't necessarily start quickly, can start slowly, but to resolve it just shift the start point of Horton's curve.

B.3.3 – Runoff
- -Hortonian
- -saturated overland flow
- -Through flow (subsurface flow)
- -Return flow
- -Groundwater flow

B.3.4 Role of macropores
B.3.5 Controls on runoff

- Hortonian overview
  - Ignore rain not higher than infiltration rate
    - Incremental hyetograph, with overlaid curve
  - Impact of Hortonian runoff
    - Flood risk – rapid surface runoff means that it is very likely to create a rapid increase in the discharge of nearby rivers
    - Erosion – particularly the case on agricultural fields or bare ground. Will create gullies and depressions, can happen very quickly? Extreme gullies can occur
  - Criticisms of Hortonian runoff
    - Assumption of homogeneous conditions
      - It doesn't take into account spatial variability, assumes that the ground it is moving over is uniform, it also doesn't take infiltration into account
    - Differences between environments
      - Horton runoff is normally the exception, not universally applicable
      - Only applicable to extreme events – hence why other models were developed – Dunne model, for forest hydrology
      - Comparison between Dunne and Horton may be questions
        - In Horton water table was constant, and saturation zone was between top and water table, and with rain saturation zone will go to about 10-15m
        - In Dunne, as the rain comes, the water table rises, it is not a fixed point. Until the water table reaches the ground, there is no water flowing in the surface.
          - Applicable to forests because infiltration capacity is way greater than agricultural fields and urban areas (except near streams
          - Which is basically part of saturated overland flow
- Saturated overland flow (runoff over saturated areas, partial contribution)
  - Dynamic concept – very important concept about this
    - Varies in time at 2 scales
      - Varies during a precipitation event
        - Saturation zone starts right near the stream, and grows throughout the rain event, as more rain falls
      - Varies between seasons (spring is the most saturated)
        - Saturated area is biggest after snowmelt, contouring the river.
        - Saturated area decreases into autumn, shrinking to the immediate surroundings of the river.

- Through-flow or sub-surface flow
    - Water flowing through the soil
    - Much slower than overland flow, and will vary a lot depending on
        - The permeability of the soil layers
        - Depth of the soil
        - Moisture conditions (antecedent, prior to wetting event)
    - Will vary a great deal though,
        - Very long lag time to peak (time between the wetting event and the peak.)
        - Very mild peak volume
- Return Flow
    - Flow that starts as sub-surface flow and returns to the surface later on
    - Why does it get forced up? It gets forced up when it reaches saturated areas (water table rises, etc)
    - Important as the water varies in composition as it flows through the soil
- Groundwater
    - Confined (fixed water table, under pressure) or unconfined aquifers (dynamic, water table can shift depending on precipitation amount)
    - Piezometric surface: imaginary surface that everywhere will coincide with the piezometric head of water in aquifer
        - //piezometric head: pressure that exists in a confined aquifer//
    - Movement from a higher hydraulic head to a lower hydraulic head
    - Hydraulic force is the driving force behind the groundwater flow, no correlation between groundwater flow and surface slope
    - Hydraulic head is the height that the water rises above the reference level
- B.3.4 Macropores
    - Relationship between capillary tension and the size of pores
    - Problems arise due to the complex relationship with the geometry of pores
        - Increase in size+ increase in connectivity of pores will decrease the capillarity of pores
        - Soil matrix: porous media
        - Effect of macropores – speeds up the flow of water in soil as it is like a mini pipe in the river- how do you know how many there are though
    - No 'simple' model such as Darcy's law for micropores
    - Types of macropores: a function of their origin
        - Fauna: tubular, near the surface (connectivity different at surface, then much below, because of spread of fauna)
        - Roots – 35% volume of soil in forest environment – tubular in shape
        - Desiccation cracks – triangular in shape, mainly found in clay
    - Macropores in infiltration fig B.3-34
        - I – infiltration by micropores
        - S – seepage, for macropores
        - P – Precipitation
        - 1 – surface
        - 2 – subsurface
        - T – time
        - Three cases
            - $P(t) < I, (t)$

      - Water absorbed by micropores
    - $I(t) < P(t) < [I_1(t) + S_1(t)]$
      - Surface flow will be local
      - Flow in macropores
        - $S_2(t) > 0$
        - $I_2(t) > 0$
    - $P(t) > I_1(t) + S_1(t)$
      - Very rare, as it is rare it exceeds both micro & macropores
      - Through flow and generalised runoff as a result
  - Overall surfaces have an inhomogeneous porosity
    - The hydraulic conductivity is highly variable
    - The velocity range is also very variable

B Water in the watershed
- B.3 Runoff: types and controlling factors
  - B.3.1 Infiltration
  - B.3.2 Estimation of the rate of infiltration
  - B.3.3 Types of Runoff
  - B.3.4 Role of Macropores
  - B.3.5 Controls of runoff

B.4 Return period and flood hydrograph
- Slides on measurement of discharge
- B.4.1 Return period

- Assignment 3
  - About runoff and return period, should be able to do it all by Wednesday. First part can be done already, 2nd part by Wednesday
  - Need to overlay rain (bar graph) over continuous function
- B.3.5 Controls of Runoff
  - Fig b.3.35 very important
    - X axis goes from arid to thin vegetation or human intervention to humid climate and dense vegetation (climate vegetation and land-use)
    - Y varies the topography and soils
      - Top: Thin soils, gentle concave foot slopes, wide valley bottoms, soils of high to low permeability
        - Concave == water table close to surface the length
        - Convex == water table is far from surface
      - Bottom: steep straight hill slopes, deep, very permeable soils; narrow valley bottoms
    - The idea on a rainfall rate/time graph for infiltration rate is to have the curve as high as possible so as to not have a huge effect
  - Going from forest to urban areas. The evapotranspiration doesn't vary a lot, but the infiltration depth varies quite a bit, as does the amount of impervious ground, leading to much more runoff in urban areas
    - Garden idea to increase infiltration during wetting events
    - To look at Philadelphia water dept. porous asphalt
- B.4 Return period and flood hydrograph
  - Terms:
    - Volume of water, which can be represented as a hydrograph: which is simplified as water at one point along a stream
    - Hydrograph; graphing the response of a basin to a precipitation or to an event
    - Discharge on y- axis, time on the y-axis
    - Measurement of Q
      - From height:
        - V-Notch Weir method (small streams)
          - A small V-Notch Weir (dam, with a v in the middle,)
            - Fairly expensive, and also requires a weather protection for instruments
          - H_e = height above the V-notch, which is normally raised to a power of 2.5

    - Stage-discharge relationship == rating curve
        - Height is a function of hydrostatic pressure, put it in stream, and baro-logger, taking atmosphere pressure, ok at easy flow, not good at high flow, hard to get there in time.
  - Salt dilution method
    - Mountainous streams typically because it is hard to measure
    - Mass balance method
    - Q = mass of salt over area. Typically measured by conductivity,
- B.4.1 Return Period (recurrence interval)
  - Definition – time interval between 2 consecutive events over a certain magnitude
    - Recurrence interval (t) is the time between of the $X >= X_t$. X = discharge / X_t = some level of discharge
    - Return Period (T) is the expected value of the recurrence interval.
      - E = expected value == is the average value over a large # of occurrences
    - T = average of t(recurrence interval) or
      - {The number of years between the first and the last occurrence of an event exceeding a certain threshold) / (# of intervals(occurrences – 1))
    - Example:
      - Year range where the occurrences> than a threshold.
      - 1977 – 1936 = 41 years
      - Occurrences = 9 so occurrences -1 = 8
      - 41 years/8 == 5.1 years
    - Exercise on pg.144
  - Concept of series
    - Complete series: all data available
    - Partial series: only above a certain threshold
    - Annual series: maximum values for each year
      - Most used in our latitude, environment Canada will preserve this (HYDAT), in the US the USGS will do the same
    - Computation of T (return period for annual max series)
      - T = (number of years in the series + 1) / rank of the event in decreasing order
    - Graphing it
      - Q on y-axis (log)
      - T on x-axis (also Log)
    - Example: 20 years in table
      - N = 20, r (event we are interested in) = 5
      - T = (20+1)/5 = 4.2
    - Probability is 1/T(return period)
  - When a river is full (all channel is filled with water) – Bankful discharge
    - Return period 1.5-2 years
    - It is normal for a river to flood, it is not a problem
  - Essential to have historical data, very important for the overall picture.
  - Assumption in stats that there is no temporal trend (stationarity), however what do we do with climate change? More extreme events with climate change

B water in the watershed

B.4 Return period and flood hydrograph

B.4.1 Return Period

Slides on floods

B.4.2 Factors affecting hydrograph

Slides on river straightening

B.4.3 Methods of hydrograph separation

C Mechanics of flow and sediment transport

C.1 Hydraulic geometry

- Return period (T) related to probability (P) T = 1/P
- What is the probability that a t-year return period will occur in the next N years?
    - Ex.
        - T = 100 years
        - N = 50 years
    - P(x> at least once in N years)
    - = 1 – (1-1/T)^N = 1-(1/100)^50 = 0.39 = 39%
- Assumptions are;
    - There is no long term trend occurring
    - Independence of events (just because one flood happens, doesn't mean that another will happen given the same input conditions, as the ground conditions are always in flux)
- When there are no gauging station:
    - Use the watershed area ratio approach
        - Ex gaged water station: drainage area = 210km^2 which is nearby and has a similar land use, then for the ungagged drainage area you of say 100km^2 you use the ration 100/210= 0.48 and you multiply the annual max Q by the ratio
- Floods
    - Very widespread flood, as it will go very far horizontally, it is only vertical distance that can help you escape
    - During a flood there can be a huge amount of sediment transported in floods.
- B.4.2 Factors affecting hydrograph
    - Basin /Watershed characteristics
        - Form
        - Size
        - Slope (topography)
        - Network structure (bifurcation ratio effects how efficient network is in transport of water
        - Speed of transfer within the network
            - Velocity within the channel
            - River straightening (particularly in agricultural watersheds) (30,000 km of straightened rivers in Quebec)
            - Problems arising with river straightening
                - Flooding, re-meandering, bank erosion
    - Land Use (affects rate f(t))
        - % of impervious surface
        - % of forest
        - Types of cultures (affecting the hydrograph)
    - Characteristics of soils (affects cumulative infiltration F(t))

- Thick/shallow soils
- Irrigation, artificial drainage
- Pressure of reservoirs
  - Human made & natural reservoirs (lakes/ marshes/ wetlands)
- B.4.3 Methods of hydrograph separation
  - Many different types of hydrographs exist
    - On yearly scale, can give an idea of the climate the hydrograph is representing
    - On a per event scale (fig B.4.10)
      - Rising limb B-C
      - Peak Flow C
      - Falling limb D-E
      - Base flow recession
      - A part that is linked to storm runoff (B.3)
  - How to separate (methods):
    - Straight line
      - From when it starts to rise to a point, anything below is base flow, above is excess flow
        - Ok for ephemeral streams, not good in humid climates
      - Delayed flow
    - Fixed base method
      - N(days) = $A^{0.2}$ in square miles
    - Variable slope (using the inflection point)
      - Use the inflection point to figure out where base flow is
- C Mechanics of Flow and sediment transport
  - To understand the action of flowing water on landscape
  - Open channel versus pipe flow
    - no constraint on water's surface
  - channelized flow vs diffuse flow
    - rivers vs no limits, very wide bed + very shallow flow (agricultural environments)
    - emphasis on channelized flow
- C-1 Hydraulic geometry
  - Relationship between channel form and discharge
    - C.1.1 Variables and coordinate systems
      - (vertical exaggeration is always there, to represent river
      - W = width [L]
      - Y, d = mean depth [L]
      - Y_{max} is max depth [L]
        - (formed channels always have a trapezoidal shape, to make calculations really easy
      - A = cross sectional area = Y_{mean} * w (assuming a rectangular shape for width)

C Mechanics of Flow and Sediment transport

C.1 Hydraulic geometry

C.1.1 Variables and coordinate systems

C.1.2 At-a-Station hydraulic Geometry

Slides on hydraulic geometry

C.1.3

- C.1.1 Variables and coordinate systems
  - Bankfull is difficult to identify, as it is not always even on both sides of the stream
  - Hydraulic radius – important concept: R = A(cross sectional area: width*depth) / P (wetted perimeter, the sides and bottom of the river; 2*depth(y) + width
    - R = W*Y / 2Y +W but because 2Y is << W it becomes R = W*Y /W = ~Y
  - Velocity
    - In 3D
      - U = longitudinal velocity
      - v: lateral velocity, sometimes W
      - W: Vertical velocity, sometimes v
      - V = Velocity sometimes
      - U = mean velocity sometimes $\bar{U}$
      - Slope is Δy/Δx; height/length = tan θ
        - Always a slope, but nothing like a hill slopecam
      - Typical slope ~ 0.001
        - Can have many slopes
          - Slope of Bed; S_0
          - Slope of water surface; S
        - Equilibrium; $S_0 = S$
      - During passage of a flood
        - When the S is $\neq S_0$
        - It is in disequilibrium, higher upstream than downstream, the adjustment of the river is erosion(degredation) downstream on the rising limb
        - Once the flood has passed, upstream from flood you are in the falling limb, the adjustment is deposition (aggradation)
      - Q = V*Y*W
    - Hydraulic geometry
      - General relationships describing the mutual adjustment between channel form and discharge (independent variable) Q = X axis
      - From regime theory (engineers came up with it)
        - Conception of irrigation channels (from Leopold & Maddock, in 1953 hydraulic geometry of stream channels and some physiographic implications USGS
      - Basic relationships
        - Q = V*Y*W
          - $W = aQ^b$
          - $Y = cQ^f$
          - $V = kQ^m$

        - All power functions log on both axis
    - Regression
        - Linear $Y = a+bx$ //Y = arith, X = arith
        - Exponential $y = ab^x$ //Y = log, X = arith
        - Power $Y = ax^b$ // Y = log, X = log
        - Logarithmic $Y = a + b\text{Log}x$, // Y = arith, X =log
    - $Q = aQ^b*cQ^f*kQ^m$
        - $Q = (ack)Q^{b+f+m}$
            - Ack == 1
            - B+F+M ==1 = rate of change
- C.1.2 At-a-station hydraulic geometry (for a X-section)
    - Leopold and Maddock averages
        - B = 0.26, F =0.4, M =0.34
    - Example 1: rectangular channel (river is entrenched in bedrock or highly cohesive banks, like clay)
        - B (rate of change of width wind change in discharge) = 0, as the slope is 0 at all three Q's
            - F+M have to = 1
    - Example 2; triangular channel (river has non-cohesive banks with gravel)
        - B>> than the rectangular case
        - F (depth changes fast with discharge change)) << than the rectangular case
    - Example 3 : parabolic channel (top part clay or cohesive silt, bottom has sand/grave, most common shape)
        - Intermediate situation between the rectangular and the triangular cases
        - Average value that was found by L&M
            - B = 0.26, F =0.4, M(velocity increases fast with discharge) =0.34
    - Link between hydraulic geometry exponents (At-a-station)
        - Linked to channel pattern
            - Rhodes diagram (Figure c.1-2)
            - At each corner the variables are at 1, distance between opposite side and corner is 1
- C.1.3 Down-stream hydraulic geometry
    - L&M average values
        - B = 0.5, F =0.4, M =0.1
    - When comparing two sections, you can't compare for a certain discharge, as the discharges increases downstream
    - You have to determine the frequency (occurrence) of a q to compare upstream/downstream often at bankfull Q 1.5-2 years

Class 16 Nov 5, 2014

C.1 Hydraulic geometry
- C.1.1 Variables and coordinate systems
- C.1.2 At-a-station hydraulic geometry
- C.1.3 Downstream hydraulic geometry
- C.1.4 Limits of Hydraulic geometry

C.2 Mean velocity at a river cross section
- C.2.1 Velocity distribution in a channel
- C.2.2 Estimation of Manning n
- C.2.3 Estimation of mean velocity at a cross section

- Downstream hydraulic geometry exponents
  - Mississippi gets deeper downstream, while St Laurence widens
- Last table in C.P.
  - Shows exponent changes linked to flood probability
    - Why do serious floods not change a lot in velocity, while frequent ones don't? because huge floods have trees and houses as bottom, reducing velocity
- C.1.4 – limits of hydraulic geometry
  - At-a-station:
    - Most cross sections are much more complex than used in this model
    - Ex. Sediments accumulate in bars, not a flat bottom
  - Downstream
    - Position of measured sections will create scatter
      - Riffles (shallow) and pools (deep) (not accounting for this)
    - The width of streams vary until they reach a confluence, then get markedly wider, and continue to vary until they reach another confluence. (downstream model doesn't account for this)
  - Main criticism
    - Should be a multivariate model of geometry of channels, and hydraulic geometry only uses Q as an independent variable, (not just Q explaining the changes in the channel
    - 2 important variables that control dimensions of rivers
      - Bank Cohesion
        - For any Q, the rivers that have a stronger bank cohesion will be narrower than rivers with less cohesion
      - Sediment transport
        - For a given Q and given bank cohesion, rivers that transport more sediment will be wider than those that transport less.
- C.2 Mean velocity at a river cross section
  - C.2.1 Velocity distribution in a channel
    - Bed + bank is where the most resistance is
      - ∑ of everything that can slow down a flow
      - Very difficult to measure
        - Local (at one point)
          - τ_o Bed shear stress
            - == ρ *g*R(hydraulic radius ≈depth)*S_0
        - Global (over section, reach of a river)

      - Manning's roughness coefficient (n)
      - Chezy coefficient (C)
      - Friction Factor from Darcy Weisbach f_0
- C.2.2 Estimation of Manning n
  - $n = (n_0 + n_1 + n_2 + n_3 + n_4)*m$
    - n_0 - Type of material
    - n_1 – Degree of irregularity of banks
    - n_2 – Variability in cross section
    - n_3 – Obstacles (roughness)
    - n_4 – Vegetation
    - m = S =Sinuosity = length of channel/valley length
      - The amount that a channel meanders, instead of a straight line, which serves to slow the velocity.
    - Isovels (lines that join areas of common velocity in a river channel)
    - Thalweg – line of maximum depth
    - All the elements are really hard to estimate, be wary to not double, if material is gravel, don't also use bank irregularity as severe.
    - Tables in C.P. are super useful, as is link in slides
    - One issue with manning n value will increase with depth? Pictures are hard because they are only one level of river flow
  - Strickler equation
    - Only for simple channels, no obstacles, no vegetation, when $Y > 10\ D_{50n}$ (median diameter)
    - $n = 0.0151\ D_{50}^{1/6}$
      - D_{50} is in mm
- C.2.3 Estimation of mean velocity at a cross section (uniform flow)
  - Equations
  - General model
    - $V = c^* (1/\Omega)\ R^{\alpha} * S_0^{B}$
      - c = constant due to units
      - Ω = resistance
      - R=hydraulic radius
      - S_0 = Slope
  - Chezy equation
    - $V = c^*R^{0.5} * S_0^{0.5}$
      - C = chezy coefficient
  - Manning's Equation
    - $V = u_m^* (1/n)\ R^{2/3} * S_0^{0.5}$
      - u_m = constant for units
      - n = normally 1 or close to
    - $V = (R^{2/3} * S_0^{0.5})/n$
  - Example Ruisseau du Sud (eastern townships)
    - We know;
      - Velocity V = 0.69 m/s
      - Depth Y = 0.38m
      - Width W = 6.10m

- Hydraulic radius R = A/P = WY/2Y+W = 0.34m
- Slope S_0 = 0.009
- n = (n_0+ n_1 + n_2 + n_3 + n_4)*m
  - n_0 - Type of material = 0.026
  - n_1 – Degree of irregularity of banks
  - n_2 – Variability in cross section
  - n_3 – Obstacles (roughness)
  - n_4 – Vegetation
  - m = S =Sinuosity = 1 minor= will not affect the calculations

Class 17 Nov 10, 2014

C.2 Mean velocity at a river cross-section
- C.2.1 Velocity distribution in a channel
- C.2.2 Estimation of Manning n
- C.2.3 Estimation of mean velocity at a cross-section
- C.2.4 Measurements devices for velocity (slides on current meters)

Assignment 4

- Finish example of Manning n
  - Ruisseau du Sud
    - V = 0,.69 m/s
    - Y = 0.38m
    - W = 6.10m
      - R = 0.34m
    - S = 0.009
    - N_0 = 0.026
    - M = 1.0
      - N_1 = degree of irregularity (banks) (if the banks are eroded or not, how much can they be eroded?
        - No major evidence of vegetation slumping into the river, so they are not eroding a lot
        - How much are the banks affecting the river, it is fairly narrow, so banks have more of an effect than say the St.-Lawrence
        - == 0.007 as a value
      - N_2 = variability of the size of the cross section,
        - Not a lot of variability
          - == 0.000
      - N_3 = Obstacles/obstructions, logs, blocks etc. effect on slowing down the flow
        - ==0.022
      - N_4 = vegetation on river bed -- effect on water flow
        - ==0.010
      - = (0.026+0.007+0.000+0.022+0.01)*1.0
        - =0.065n
    - V = $(0.34^{2/3} * 0.009^{0.5})/ 0.065$
      - V estimated = 0.071 m/s
      - V = 0.069m/s == Measured

- Direct Measurements at a point
  - Velocity changes from zero to fastest when measured at different heights above the bed
    - Velocity is computed from velocity profile
      - For ex. @ 0.4m go to height and draw straight line across to velocity curve only if above 50cm, if below use :
        - Average of 2 measurements, at 0.2y, and 0.8y
    - Discharge at a cross section
      - From mean velocity (manning n's
      - From detailed measurements (current meters)

        - Q = VWY
            - 2 ways to find average depth
                - Average of several depth measurements
                - Count squares -> Area/width
        - Get many panels of a certain width and depth, and a velocity measurement, and result is many small q values, and then the Q is sum of all small q's
- Measurement devices for velocity
    - 1. Propeller current meters (Price, Swoffer)
        - Used often infield
        - Number of rotations is proportional to velocity
        - 1-Dimensional
        - Advantages
            - Very simple
            - Very 'cheap' 4000$
    - 2. ECM current meters (electromagnetic current meters)
        - Used in the field
        - Principle based on the distortion of the electromagnetic field (field generated in the center, and the deformation is deformed by flow)
            - Faraday's law: V proportional to amount deformed
        - 2-Dimensional
        - Up to 20Hz (20 measurements/second)
            - Measures turbulence
        - Advantage: Cost 7000$ dollars
        - Disadvantage: contamination depending on where you are geologically speaking, due to iron etc.
    - 3. Acoustic Doppler Velocimeter (ADV)
        - Can be used in the lab and field
        - Principle is : V is proportional to Frequency shift
            - Doppler effect
        - Measurement in 3-dimensions
        - Up to 25 Hz (turbulence)
        - Small measuring volume, quite precise (1cm^3)
        - Cost is around 15,000$
    - 4. ADV profiler (Vectrino II)
        - Only one measurement at a time, however the ADV profiler will take many measurements at one time
        - 3 cm profile, but only useful in the lab
        - 25,000$ cost
    - 5. Laser Doppler Anemometer (LDA)
        - 2-Dimensions
        - V proportional to shift in frequency of laser beam
        - Only used in lab
        - 200,000$
        - 200Hz measurements, turbulence measured very precisely
    - 6. Acoustic Doppler Profiler (ADP)
        - Used a lot in the field, typically from a boat

    - 2Hz maximum, (typically done for mean velocity and not turbulence, as it is not good for measuring turbulence)
    - 70,000$
- 7. Particle image Velocimeter (PIV)
    - Mainly in the lab, possibly in the field,
    - Takes many pictures at one time, and it measures the movement of particles from one image to the next
    - Large scale PIV when in rivers, difficulties in high flow, as hard to see

Class 18 Nov 12, 2014

C.3 Forces involved in water motion
- C.3.1 Forces inducing motion
- C.3.2 Resisting forces (friction)
- C.3.2 Ratio of forces
  - Slides on supercritical flow

- Forces involved in water motion
  - Looking at what is going on from upstream to downstream
    - First group inducing motion (F→)
      - Gravity, a function of the slope
      - Pressure, a function of height of water, acting to accelerate
        - Always from higher pressure to lower pressure
    - Second group introducing resistance (F←)
      - Friction of fluid
        - Internal resistance: viscosity (μ)
        - Turbulence
      - Pressure
        - Acting to decelerate the general flow, creating a force in opposite direction.
    - 3^{rd} group inducing changes in direction of flow (F^{o})
      - Centrifugal forces
        - Important in meanders
      - Surface tension
        - On the surface
      - Coriolis
        - Function of the earth's rotation, only for enormous rivers
- C.3.1 Forces inducing motion
  - Gravity
    - F = m*a = m*g
  - Pressure
    - Hydrostatic pressure
      - Caused by the weight of water above a point, like atmospheric pressure
      - Pressure = γ y
        - Y = depth below water surface
      - Proportional to the depth below water surface
      - Force pressure/unit mass
        - Fp= ($\gamma\Delta$y*WY)/mass
          - Mass = ρ*vol
            - Vol = X*Y*W
        - Therefore Fp = $\gamma\Delta y/\rho x = g\Delta y/x$
      - Pressure along a curved streamline, there will be a difference in pressure from one bank to another, which is a result of the centrifugal forces of the meander, which will result in a piling up (higher water surface) of water on the outer bank of the meander. (deeper, and sediments deposited on inner bank)
    - Pressure around a particle

            - Less pressure on top of particle, more pressure beside it, helping it to rise as pressure moves from higher to lower. Called LIFT
- C.3.2 Forces resisting motion (friction)
    - Viscous Force (shear stress) (τ)
        - $\leftarrow\tau = \leftarrow F_v/A = \mu*(dv/dy)\rightarrow= \mu *V\rightarrow/y = ((V\rightarrow/y)*\mu *(x*w))/\rho*x*y*w$
        - $=V\rightarrow * \mu / \rho *y^2$ && $\nu= \mu/\rho$ therefore == $\leftarrow F_v = (\nu * V\rightarrow) / y^2$
    - Turbulent force (also called inertial force)
        - $\leftarrow \tau = \varepsilon * dv/dy = \varepsilon V\rightarrow/y$
            - ε : Viscosity due to turbulent mixing (eddies)
            - definition: $\varepsilon = \rho * V\rightarrow*y$
        - $\tau = F_t/A ==V^2/y$
- Ratio of Forces
    - $F_g\rightarrow$
    - Friction = Fv/Ft
    - Reynolds number (1883) = Ft/Fv = V*Y / ν == Re= V*l(usually R (hydraulic radius)/ν
        - Re < 500 : Laminar flow (with viscosity dominating)
            - Dye at different levels, it will flow in 1 dimension
        - Re > 2000: Turbulent flow dominates – Intense mixing
            - It will flow in 3 dimensions
        - Between the two is transition
        - In natures Re are typically > 30,000 way above the turbulent flow threshold
    - Ex: V = 0.5m/s, Y = 0.4m T = 10C –$\nu = 1.786 *10^{-6} m^2/s * 0.7315$
    - Turbulence matters, all rivers are turbulent
- Ft/Fg = $(V^2 / y)/g$ = = Fn = V/ (g*y)^0.5
    - Fn < 1 – Subcritical
    - Fn = 1 – Critical
    - Fn > 1 – Supercritical
- Going from subcritical to supercritical
    - Nothing really happens
- Going from supercritical to subcritical
    - Have a hydraulic jump, which brings in a lot of oxygen, which increases the water quality, for us and for aquatic life
- When you combine both the depth and the flow, you get:
    - Change of velocity with time
    - Change of velocity with space
        - No change velocity with space: uniform flow (only valid for short reaches)
        - No change in velocity with time: steady flow (only valid for short time periods)
        - Change in velocity with space: varied flow (gradual or rapidly)
        - Change with velocity with time: unsteady flow
        -

Class 19 Nov 17, 2014

C.3 Forces and classification end note
C.4 The boundary layer of a uniform flow
C.4.1 Laminar Flow
C.4.2 Turbulent Flow
C.4.3 Computational Examples

- C.3 Uniform steady flow
  - No change in V or Y in space and time, there is no acceleration
    - Meaning that we can use the concept of force balance == put an = sign between the forcing accelerating and resisting motion
    - i.e. F→ == ←F defined as Gravity = Friction //Viscosity + turbulence//
  - laminar case
    - Fg→ == ←Fv
  - Turbulent case
    - Fg→ == ←Ft
- C.4 The boundary layer of a uniform flow
  - Definition:
    - The portion of a fluid where the presence of a solid boundary (in a river=bed) affects the flow.
- C.4.1 Lamina flow
    - Fg→ == ←Fv
  - 2 important concepts
    - Shape of velocity profile: Parabolic
      - v for velocity profile
      - $v = ((g*S_0)/\nu(nu))*(Yy - y^2/2)$
        - Y == mean flow depth
        - y ==height above bed
        - v ==velocity at the height above the bed
        - V == mean velocity
        - ν == nu
    - Bed shear stress
      - $\tau = \rho g Y S_0$
        - ρ== Rho = mass density
        - g == gravity
        - Y ==mean flow depth
- C.4.2 Turbulent Flow
  - Natural rivers is what it applies to
    - Prandtl (1875-1953
      - Really did a lot for turbulent flow, explaining/defining ε
      - ε(turbulent Flow) – ρl^2 dv/dy
        - ρ == mass density
        - l == mixing length
        - dv/dy == change in velocity profile
    - He made 2 assumptions
      - Assumption 1
        - l = k*Y

        - k ==constant
        - Y == Flow depth
      - $\varepsilon = \rho k^2 Y^2 dv/dy$
      - take home message, mixing depends on the depth
    - Assumption 2
      - Shear stress throughout the flow == constant and equal to laminar value
      - $\tau = \rho gYS_0$
  - shape of the profile is logarithmic
    - $v = 1/\kappa(gYS_0)^{1/2} \ln (y/y_0)$
      - κ = von Karman constant ≈0.4
      - $(gYS_0)^{1/2} = v_k$ = frictional velocity (shear velocity)
      - y_0 = Height above bed where velocity is 0
        - $y/y_0 = 1$ when the $y= y_0$ so that ln(1) ==0
        - $y_0 \neq 0$ has to be higher.
    - $v = 2.5 v * \ln (y/y_0)$
      - law of Prandtl-von Karman
      - universal law of velocity distribution
      - law of the wall
  - 2 cases
    - Smooth channel (laboratory, flow over plexiglass)
      - 3 zones
        - Viscous layer
        - Transition layer
        - Zone where turbulence dominates
    - Rough channel (rivers, even if sand/clay it is still rough)
      - Roughness =function of
        - Skin friction (grains)
        - Morphological friction (larger forms such as dunes, ripples, pebble clusters)
    - Additive friction
      - Have to know something about the form
      - k_s ==effective roughness height [L]
      - height of particles adjusted for the form
    - ********IMPORTANT********
      - y_0 is $=0.033*k_s$ Roughness height)
        - OR
      - $k_s == 30* y_0$
- C.4.3 - Computational Examples
  - Key question to answer: what is the use of the velocity profile? Universal law?
    - Compute the mean velocity at a point
      - $V = 2.5v *(\ln(Y/y_0)-1)$
        - Y = mean flow depth
      - We can replace the y in law of the wall by a fraction of flow depth?
        - =bY (a fraction b of the flow depth Y
        - By combining

- $2.5v * (\ln(Y/y_0)-1) = 2.5 v * \ln(y/y_0)$
  - Simplifies to $\ln(1/b) = 1$ b :1/b = e: b == 1/e == 0.37 ≈0.4 which is why we use 0.4 as a measurement to get mean velocity ***********************
- Compute bed shear stress (τ)
  - Need to find the y_0 and v_k
  - At least 5/6 methods
  - This is the method to use:
    - Regression
      - Important to figure out which is the dependent and independent variable. The independent variable causes the change in the dependent variable
      - However the standard is that the independent variable is on the x-axis, needs to be this way for a regression analysis, which is the method to find y_0
      - Use the graph with the ln(y) on x-axis to find where $v_k = 0$ and do $\ln^{-1}$(value found)
    - Mathematically regression between v and ln(y)
      - $v = a+b \ln(y)$
      - $\ln y_0 \rightarrow \ln$ when $v_k == 0$
      - $0 = a+b \ln(y_0)$ $\ln y_0 = a/b$ (y intercept / regression slope
        - $y_0 = e^{(-0.484/0.085)} = 0.0034$m
    - k_s = roughness height
      - =30 y_0 in this example == 10.2 cm
      - Which is D84 meaning that 84% of particles are smaller than this. This means that it is probably a gravel bed
      - Use the phi scale (φ) = $-\log_2 d$ where d: diameter (mm) so $d = 2^{-\varphi}$

C.4 The boundary layer of a uniform flow
- C.4.1 Laminar Flow
- C.4.2 Turbulent Flow
- C.4.3 Computational examples
- C.4.4 Complications within the boundary layer

C.5 Sediment Transport
- C.5.1 Sediment Transport in Rivers

- Turbulent flow
    - Regression equation
        - $v = a + b \ln(y)$
        - $y_0 = e^{-a/b} = 0.0034$m
        - $Ks = 30^* y_0 = 0.102$m ≈D84
    - Really not simple to measure the grain size, nor quick, but very useful, and the estimation can be made if velocity is known
  - Estimation of (v^*) (friction velocity)
    - $\tau = \rho (v^*)^2$
        - law of the wall
            - $2.5 (v^*) \ln(y/y_0)$
    - $(v^*) = (v/2.5) *(1/\ln(y/y_0))$
    - $= 0.4v/ \ln(y/y_0)$
    - $= 0.4 (a + b \ln(y)) / \ln(y) – \ln(y_0)$
        - $= 0.4 (a + b \ln(y)) / \ln(y) – (-a/b)$
        - $= 0.4 (a + b \ln(y)) / a/b + \ln(y)$
        - $= 0.4 (a + b \ln(y)) / 1/b + (a+ \ln(y))$
    - $== 0.4b$
        - b == regression slope =0.085
    - $(v^*) == 0.4b ==0.034$m/s
    - $\tau = \rho (v^*)^2$
    - $\tau = 1000 (0.034)^2 = 1.16$N/m^2
    - friction velocity related to the force moving particles
- C.4.4 Complications within the boundary layer
        - Consequences on velocity profile
  - Flow Separation
    - Non-logarithmic profile
    - Inside Dunes of sand water flow going upstream, in opposite direction of flow,
  - Gravel bed rivers
    - Profile with 2 logarithmic sections
        - T' - Skin friction (grains) is the dominating force along the bed
        - T" -Morphological friction → pebble clusters
            - Large obstacle of pebbles
            - Leads to additive friction
                - T = t' +t "
        - 2 slopes as a result of the pebbles
        - One due to skin friction, the other due to morphological clusters
        -

************General rule using the velocity profile: Only use the bottom 20% of the velocity measurements to compute the regression slope. For sampling design, take as many points close to the bed. Applies to both gravel and sand beds***************

- Turbulence within the boundary layer
  - Velocity will vary in 3-directions
    - Horizontal
    - Lateral
    - Vertical
    - Time (all above will vary in time)
  - Turbulence is an exchange of momentum (mass*velocity) in the flow
  - Presence of bursts and sweeps
    - In constant cycles
      - Cycles are close to the bed, as are bursts and sweeps
    - Logarithmic profile only exists as an average
    - Measuring the velocity profile, a device will show burst and sweep cycles, deviating from an average line, in all 3 dimensions, the average line is the velocity profile,
  - Interesting to know that through visualization, we could see there are events going down and up, while extremely complicated, is still structured to an extend
  - Can explain ejections and sweeps, at a tiny scale though. Very important to understand sediment transport.
  - Happens in tiny scale but also larger bursts that can be scaled up to very large in the river.

- C.5 Sediment transport
  - Key for environmental impact of sediment transport
    - Will affect
      - Erosion (degradation)
      - Deposition (aggradation)
  - Initiation of motion → transport
    - Fall accumulation
  - Problems of soil+ bank erosion
    - Brahmaputra – 10-20m/ year of bank erosion
  - Complexity
    - Why? Because of the interaction between particles and a fluid
    - Difficulty in measuring sediment transported as it varies
      - Temporally
      - spatially
    - integration of large number of systems (hill slopes, streams, sediment basins
    - role of external variables
      - sediment availability, sometimes there won't be many sediments available whereas at other times there may be\
      - erosion
      - temporal changes
- C.5.1 Sediment transport in rivers

Class 21 Nov 23, 2014

Assignment 5
C.5 Sediment transport
    C.5.1 Sediment transport in rivers
        C.5.1.1 Types of transport
        C.5.1.2 Initiation of motion: shields diagram
        C.5.1.3 Bedforms

- Assignment 5
    - Using law of the wall use an equation from it to get mean velocity.
- C.5.1 Sediment transport in rivers
- C.5.1 types of transport
    - From the origin of material
        - Washload
            - Anything other than the bed
                - Banks, agricultural runoff, hill slopes
                - Always fine material, always moving in suspension
        - Bedload (bed material)
            - Material moving on the bed
    - From the transport modes
        - Suspension
        - Traction (bedload)
        - Solution (dissolved)
        - **see slide
    - Definitions of key terms
        - Competence
            - Maximum grain size that a river is capable of eroding and transporting under varying conditions
        - Capacity (total load, or sediment discharge)
            - Total load that a river can carry under varying conditions
        - Predicting both of these are the task of hydro-geo-morphologists, very difficult to do
        - The problem/hard thing to do is predict both competence and capacity, given the depth, velocity, width, friction velocity(v*), (τ)
            - Very difficult
            - ******IMPORTANT FIGURE C.5.5*****
                - Concept of critical shear stress (or friction velocity)
                    - Critical means that it refers to the initiation of motion
                    - Less than 1 no transport
                    - U*/U*0 = critical friction velocity
                    - Close to threshold of motion
                - How to read graph?
                - Find point and see where it is. Take the intercept of the curves, and go straight line to axis, and that represents the percent of particles being carried by the method
- C.5.2 Initiation of particle motion
    - Based on the shields diagram approach
        - Principle of force balance between

            - Movement
            - Resistance
        - Critical shear stress is a function of the diameter
- Looking at the grain level, not the whole river
    - 3 forces to look at
        - Gravity ↓
            - Submerged weight of grain
        - Drag→
            - Change in pressure between upstream and downstream part of the grain
        - Lift↑
            - Change in hydrostatic pressure between the bottom and top of the particle //-->Bernouilli effect<--//
        - 4^{th} force when diameter <0.006mm
            - Electrostatic cohesion force
    - 3 forces F_g, F_l, F_d,
        - $F_g = K_1(\rho s-\rho)g\ d^3$
            - K_1 = proportionality constant = pi/6 (volume of sphere)
            - ρs – mass density of sediment
            - ρ mass density of water
            - g = gravity
            - d^3 = diameter ^{3}
        - F_l && F_d
            - $\rho * v^{*2} * d^2 / 2$
        - F_e erosive force = = $F_l + F_d$
        - Motion will occur when Fe > Fg
            - Non dimensional ratio :θ_e = Fe/fg (elimate constants
            - $\theta_e = \rho * v^{*2} * d^2 / (\rho s-\rho)g\ d^3 = \rho * v^{*2} * d^2 /(\gamma_s - \gamma)d^3 = \rho * v^{*2} /(\gamma_s - \gamma)d == \tau$
- Shields (1963)
    - Experiments to find critical θ_e (θ_{ec})
        - For different diameters (spherical)d
        - Created graph of θ_{ec} vs $f(R_e)$ function of erosive Reynolds number (also looks like = D/δ_o)
        - $R_e = v * d / \nu$ (kinematic viscosity)
        - Log axis for graph
            - On left hydraulically smooth, on the right it is rough, rough is natural, so use the right size
        - On the right, when it is hydraulically rough, it flattens out, becomes constant
        - Value used, and the one to use (in CP) is $\theta_{ec} = 0.044$
            - For a fully rough flow: θ_{ec} = 0.044 = constant
            - $\theta_{ec} = \tau_{oc} / (\gamma_s - \gamma)d$
                - $\tau_{oc} = \theta_{ec}\ (\gamma_s - \gamma)d$
                    - $\gamma_s = \rho_s g = 2650 * 9.8 \approx 26000$
                    - $\gamma_s = \rho g = 1000 * 9.8 = 9800\ N/m^3$

- τ_{oc} = 0.44 (26000-9800)d
  - =713(d)
    - d in meters
- REMEMBER
  - Bed shear stress (τ_o)
  - Measured/estimated by
    - Velocity profile
    - ?
- Criticisms of shields diagram
  - Key ones
    - Armouring of a bed In gravel bed rivers
      - Many large but relatively heterogeneous particles
      - Armouring means that coarser materials on the surface, and finer below, and the coarser materials trap the fine materials below
      - Highly heterogeneous at the surface,
        - The fact that they are trapped is the concept of equimobility
        - Idea that the constant value of θ_{ec} may not really be constant, as it is not always d that is the force preventing movement
    - Turbulence
      - Assuming a mean velocity, however there is a lot of fluctuations in velocity
- Emriver.com
- C.5.1.3 Bedforms
  - A lot of practical implications
    - Obstacle for navigation
      - Dunes > 10m
    - Determine flow resistance
    - Complicates sediment transport prediction
    - Stratification
      - Link between amplitude and water depth
  - Sequence (↓ (stream power varies down list)
    - Plane bed (no transport)
    - Ripples
    - Dunes
    - Upper stage plane bed
    - Antidunes (large oscillations)

C.5 Sediment transport

- C.5.1 Sediment transport in rivers
    - C.5.1.1 Types of transport
    - C.5.1.2 Initiation of motion: shields diagram
    - C.5.1.3 Bedforms
    - C.5.1.4 Use of Shields diagram to design channels
    - C.5.1.5 Measurement and estimation for bedload and suspended load (capacity)

- C.5.1.3 Bedforms
    - Sand bed/fine sediments
        - Increase in stream power, and as you increase the sequence is
            - Ripples
            - Dunes
            - Upper stage plane bed
            - Anti-dunes
        - Stream power = $\Omega = QS_0\rho g$
        - Unit stream power $\omega = \Omega$/width = $QS_0\rho g$ / W = $S_0\rho gWYV$ /W = $S_0\rho gYV$
            - $Y \approx R$ so $YS_0\rho g = \tau$ so unit stream power = τV
    - Anti-dunes
        - Similar shape to dunes, however
            - Dunes migrate from upstream to downstream
        - Anti-dunes move from downstream to upstream
            - Cause a lot of water surface deformation
            - High Froude number, over 1, with sand, actually quite rare in nature, as normally sand bed are way downstream and deep water
            - Median fall diameter = median diameter*****assignments and exam
    - Shield diagram
        - Ripples occur with large variation with stream bed, but not large grain size
        - Plane are the triangles
    - Difficult to model what is on the bed of the river, as you can't see the bottom when looking
- C.5.1.4 Using shields diagram to design channels
    - Example: task is to design a channel that can carry a discharge of 10 m^3/s
        - Conditions:
            - Without causing sediment transport
            - Bed stable → no bars, →avoid maintenance (cost)
            - Width as small as possible
            - Rectangular channel with concrete vertical banks
            - Minimize loss of agricultural land
            - Maximize depth
            - Slope of channel = slope of valley = 0.001
            - Sediments will be those found in the valley D_{50} = 12mm
        - What are the optimal dimensions?
            - D_{50} = 12mm == 0.012m, S_0 = 0.001, Q = 10 m^3/s
                - No sediment transport
                    - τ_0 (ρgYS_0) =< τ_{0c} (713*d critical)
                    - τ_{0c} 713*d_c = 713 * 0.012 = 8.56 N/m^2
                        - if above this value sediment transport will occur

            - $\tau_{0c} = \rho g R S_0 = \rho g Y S_0$
                - maximize Y so $\tau_0 == \tau_{0c}$
            - $Y = 8.56\ N/m^2 / \rho g S_0 = 8.56/9800*0.001 = 0.87m$
        - $Q = 10\ m^3/s = VYW$
            - Know Y, but V&&W are unknown
            - $V = R^{2/3} *S_0^{1/2} / n = Y^{2/3} *S_0^{1/2} / n$
                - For the n you can use Stickler, because the sides are concrete, and no extra resistance
                - $n = 0.0151 *D_{50(mm)}^{1/6} = 0.0151* 12^{1/6} = 0.023$
                - Subbing n value
            - $V = Y^{2/3} *S_0^{1/2} /n$ $V = 0.87^{2/3} *0.001^{1/2} /0.023$
            -
            - … W == 9.20m
- C.5.1.5 Measurement and estimation of bedload and suspended load transport (capacity)
    - Instruments and methods
        - Bedload
            - Indirect measurements
                - Particle tracers
                    - At a confluence, can measure mineral differences
                    - Passive Integrated Transponders (PIT) tags
                - Acoustic
                    - Sound of the noise made by the sound of the rocks hitting each other
                        - Some equation to calculate transport as a function of noise
                - Migration of bedforms
            - Direct methods
                - Fixed traps
                    - Put a trap in river and see what falls into it
                - Mobile
                    - Baskets placed on the bed, catching sediments that go through
                    - Helley-smith sampler
        - Suspended load
            - Really easy to measure
            - The same amount at any depth being transported, just take a water sample