Fluvial Geomorphology

I. Introduction
- A. Key Terms
  - 1. Fluvial = "river"
    - a. channelized, flowing water
      - (1) water in liquid state
      - (2) fluid (changeable shape)
    - b. Driving Mechanisms
      - (1) Solar Energy (climate / hydrologic cycle)
      - (2) Gravity ("water flows downhill")
- B. Water Budget
  - 1. Moisture Inventory:
    - a. Oceans: contain 97% of earth's water
    - b. Glaciers: 2% of all moisture, comprising 75% of worlds fresh water
    - c. Ground water: 0.5% of total
    - d. Surface Water: 0.2%
    - e. Soil Moisture: 0.1%
    - f. Atmospheric Moisture: 0.0001%
    - g. Biological Water: negligible
- C. Hydrologic Interactions
  - 1. Stream Discharge = climate controlled
    - a. rainfall
    - b. snowmelt
    - c. groundwater discharge
  - 2. Discharge = volume of water flow per unit time

II. Variables of the Fluvial Process
- A. Water Budget
  - 1. Input Mechanism into surface water process = atmospheric precipitation
    - a. Precipitation = runoff + interception + storage
      - (1) Interception = evapotranspiration + evaporation + infiltration
      - (2) Storage = groundwater and/or snow pack and ice
  - 2. Precipitation: atmospheric moisture release (rain/snow fall)
    - a. Regional climatic and seasonal control on amount in any given region
      - (1) Storm/precipitation cycles
        - (a) Intensity: volume precip / unit time (> volume/time > intensity)
          - i) rainfall volume measured in inches of rain
          - ii) may graph time vs. inches of rain
        - (b) Recurrence Interval = statistical chance of a storm of a given intensity occurring within a prescribed time period

i) RI = $\frac{\text{Total No. of Years of Record}}{\text{No. Storms > Given Intensity}}$

a) e.g. 20 RI over 100 years observation = 5 occurrences

b) Generally the larger the event, the greater the recurrence interval

(c) Duration: length of storm occurrence

i) Intensity inversely proportional to duration and RI

a) High intensity, long duration storms will produce the greatest amount of geomorphic change to the landscape

3. Interception

a. interception of rainfall by plants, leaves, groundcover prior to reaching the ground

(1) Interception = "energy dissipator" in terms of rain fall impact on landscape (reduces erosion rates)

b. Evapotranspiration: atmospheric evaporation of moisture directly from plant tissue and/or in-take of moisture into plant system prior to reaching ground surface

(1) Foliage Evaporation = function of air temp. and humidity

c. Amount of interception = function of:

(1) type and species of plant cover

(2) density of foliage/plant cover

d. Approximating Regional Interception

(1) Measure total precipitation for drainage basin

(2) Measure total stream discharge at mouth of basin

(a) difference ~= interception + infiltration

(b) generally difficult variable to measure

4. Infiltration

a. water/precipitation that seeps into soil/subsurface rock

b. Infiltration function of:

(1) vegetative cover

(2) soil permeability/porosity

(3) slope grade

(4) moisture content of soil

c. Porosity and permeability

(1) Porosity: ratio, in per cent, of the volume of void space to the total volume of sediment or rock

(2) Permeability: the degree of interconnectedness between pore spaces and fractures within a rock or sediment deposit. A measure of the capacity of a porous material to transmit fluids

5. Rainfall-Runoff Relations

a. Runoff = free water flowing on continental surfaces of earth

b. Runoff = Total Precipitation - (infiltration + evapotranspiration)

B. Surface Water Flow and Erosion Processes

1. Rain impact or splash erosion

a. Effectiveness influenced by

(1) presence/absence of vegetation

(a) >vegetative cover, < erosive potential

(b) moisture content of soil

i) >saturation, > erosive potential as infiltration rates decrease

2. Sheet Erosion-

a. Horton overland flow (sheet flow = unchannelized)

(1) sheet flow of water over the surface of the earth, carrying loosened earth materials with it.

(a) e.g. parking lot during rain storm

(2) As overland flow continues downslope, the > in volume transforms the flow into channelized flow or rilling

(3) side slopes / heads of hollows = sheet flow

3. Rill Erosion-

a. concentrated flow pattern in numerous parallel seams flowing downslope, rills may coalesce into larger features known as gullies

4. Gully Erosion-larger, channelize flows carrying the potential for large amount of sediment.

a. Rill and Gullies common in semi-arid areas with sparse vegetative cover and high erosion potential.

b. Deforestation and devegetation can result in greatly accelerating the erosion process.

5. Erosion by stream flow: enlarge volumes of flowing water in large stream and river channels greatly increase the capacity to do work in form of erosion and transportation.

a. Hydraulic Shear Force- shear force exerted by moving water on sediment particles, has drag effect on moving sediment. Can result in considerable bank and channel floor erosion.

b. Abrasion- impact from collisions of pebbles and boulders during stream transport result in physical fragmentation of these sediment, gradually increasing roundness and decreasing grainsize down stream

c. Corrosion- chemical solution action via hydrolysis

6. Hierarchy of Runoff Processes

a. Rills and rivulets: small scale channels of surface runoff (inches wide and inches deep)
(1) found on upper portions of hillslopes
(2) servicing runoff only during precipitation events

b. Gullies: medium scale channels of runoff (on scale of several feet in width and depth)
(1) upper to lower portions of hillslopes
(2) servicing runoff only during precipitation events

c. Open Stream channels (scale of several feet to 10's of feet)
(1) major sites of surface runoff
(2) In humid areas, sites of year round flow
(3) may be ephemeral in arid areas

d. Overland Sheet Flow
(1) sheets of runoff freely flowing, unchannelized over the landscape.
(a) common under saturated ground conditions or very intensive rainfall events.

7. Quantifying Channelized Runoff

(1) Discharge: volume of flow/unit time:

$Q = VA$ **$V = L/T$** **$A = wd$** where,

Q = discharge (L^3/T) V = average velocity (L/T) A = cross-sectional area (L^2)
w = channel width d = channel depth

(a) As Q>, V> in channelized flow, i.e. stream flow is faster during flood periods

(2) Wetted Perimeter = wetted portion of channel base and sides

(a) $P = 2d + w$

(b) wetted perimeter = zone of friction interface between flowing water and channel boundaries

i) water velocity lowest around margins of channel (due to friction), highest in central portion of channel

(c) Hydraulic Radius of Channel: R

R = A/P (L)

(d) Manning Equation

$$v = \frac{1.49\, R^{0.66} S^{0.5}}{n}$$

where v = mean velocity, n = coefficient of roughness R = hydraulic radius S = slope

C. **Stream Discharge and Flooding**

1. Gaging stations: measure discharge of stream/river over period of time (daily, monthly, annually)

a. RI = Recurrence Interval of Discharge Data =

$$\frac{\text{Total No. of Years of Record}}{\text{No. of Discharge Occurrences} > \text{Given Value}}$$

b. Discharge Observations (Y axis) vs. Recurrence Interval (X axis)

c. Flood periodicities and frequencies of occurrences are important calculations for watershed planning, land use analysis, and emergency management operations

D. **Water Motion and Velocity**

1. Water Motion
a. Potential Energy = function of height of water mass above base level
b. Kinetic Energy = hydraulic energy of flowing water

(1) Ep converted to Ek as water drops under force of gravity

(2) "Energy Expenditure" - Ek is dissipated largely as frictional energy
(a) internal shear friction between water molecules
(b) external shear friction with channel sides and bottom

i) frictional shear applied to loose particles is fundamental component of sediment transportation

ii) velocity is controlled by frictional shear
   a) friction defined by n = roughness coefficient

c. Force of water = capacity to do work (i.e. flow, erode, transport)

$$\mathbf{F_p = F_g \sin (q)}$$

where F_p = force parallel to channel bottom/slope
F_g = force of gravity, perpendicular to center of earth
theta (q) = slope angle

(a) as slope angle (i.e. gradient) increases, Force and velocity increase

(1) <u>Patterns of Shearing and Slope</u>.
   (a) <u>Slope:</u> resting slope of particles may be inclined or horizontal
   (b) <u>Gravity Shear:</u>
      i) Tangential Force (gt): acts parallel to slope on inclined planes

   (c) Resistance to Gravitational Shear: Frictional forces (electrostatic, surface-contact roughness, and gn), thought of as a force parallel to slope, directed upslope.
      i) If Frictional force > gt = no sediment movement
      ii) If Frictional force < gt = sediment movement

d. Momentum = tendency of a moving mass to remain in motion
   (1) M = mass x velocity(as mass or Vel > , M >)

e. Velocity-depth relations
   (1) essentially frictional forces are greatest around channel perimeter

   (2) water velocity is slowest along bottom of channel and along channel sides
      (a) water velocity greatest along central/interior portion of channel above channel floor

III. Introduction to Fluid Mechanics

(1) Fluid Properties: Two most common fluids = air and water

   (a) <u>Viscosity</u>: measure of the resistance of a fluid to change shape (i.e. strain). May vary as function of temperature, >T,<V

(b) Suspended sediment flows (e.g. mudflows) can become very viscous in nature.

(c) Newtonian Fluid: e.g. water, fluid does not deform plastically, i.e. stress is applied and strain occurs instantaneously.

(d) Bingham Fluid: e.g. viscous lava or debris flow, fluid deforms plastically, i.e. a certain magnitude of yield stress must be applied before strain occurs.

(e) Thixotropic substances: those that display variable viscosity dependent upon amount of shear stress applied.

(2) Density: mass per unit volume (M/L^3). May also vary as function of temperature, > T,< D

(3) Fluid Flow: a function of shear displacement of fluid

(a) Laminar Flow: fluid flow in which shear surfaces conform to the shape of the boundary of the fluid

i) Laminar Flow Regime: at low shear rates, with relatively high resistance to shear

ii) resistance to shear > with > viscosity

(b) Turbulent Flow: fluid flow is characterized by vortices and eddies,

i) Characterized by higher rates of shear

ii) Turbulent flow is highly effective as a transport mechanism in that "up eddies" provide a vertical lift component for sediment transport.

iii) Helicoidal Flow Tubes: special case of turbulent flow involving spiraling component of flow in longitudinal direction of movement.

(c) Reynolds Number: Analytical technique defining the conditions of laminar vs. turbulent flow

Defined by: $Re = \frac{pdu}{v}$ where :

p = fluid density, v = viscosity of fluid, d = depth of flowing water, u = velocity of flowing medium, Re = dimensionless number defining laminar vs. turbulent flow.

for pipes and open channel, transition from laminar to turbulent flow: Re = 500-2000.

(d) Froude Number: dimensionless number defining the effect that gravity plays in causing flow

Defined by: Fr = u/(SQRT(dg)) where:

u = velocity of flowing medium, d = depth of flow, g = gravitational acceleration

Essentially = ratio of flow velocity to the velocity of a small wave created in the flow (as a function of gravitational attraction).

Fr < 1, then wave velocity (under gravity) > flow velocity = "tranquil flow", e.g. waves from a pebble thrown into the flow can propagate upstream

Fr > 1, then wave velocity (under gravity) < flow velocity = "rapid" flow. e.g. waves from a pebble thrown into the flow would only propagate in direction of flow.

Fr=1 critical flow

(4) Boundary Conditions: comprised by physical boundaries of the fluid flow system (e.g. stream channel), i.e. points of friction interface.

(a) Composition of substrate: e.g. soft sediment vs. bedrock

(b) Surface roughness: > surface roughness, > flow turbulence. Create lower bounding layer of increased friction, decreased velocity, and > turbulence.

IV. Slope as a Controlling Variable

A. As slope or gradient of channel increases... velocity increases

a. As slope and velocity increase: the capacity of stream to transport sediment also increases

b. in formula Q =wdv

(1) if Q is held constant, then an increase in velocity due to increased gradient, would have to result in a corresponding decrease in d if constant Q is to be maintained

(a) Hence, and increase in slope, at constant Q, would result in increase in velocity, with decrease in depth

i) higher velocity and < d would result in greater shear force on channel, and results in channel erosion and downcutting

V. Sediment Load and the Fluvial Process

A. Sediment Supply to Rivers

1. Function of:

a. Topographic Relief

> Relief, > gravity > denudation rates

b. Hillslope geology/lithology: dictates composition of sediment load

c. Climate: influences weathering process and vegetation

d. Vegetative cover: stabilizing force on hillslope

(1) low vegetative cover: high hillslope sediment yield

(2) High vegetative cover: low hillslope sediment yield

2. Types of Sediment Load

a. Dissolved Load: dissolved ions in solution

b. Rafted/Flotation Load (e.g. organic debris/garbage)

c. Suspended Load

(1) fine sediment carried within body of fluid medium

(2) dependent on water velocity and grain size

(a) coarser the sediment, > velocity required

d. Bed Load: very coarse sediment transported along the channel substrate under shear force

e. Capacity vs. Competence of a Stream

(1) Capacity- expression of the potential load that a stream can transport, in vol. of material per unit area.

(2) Competence- the largest particle diameter that the stream is capable of transporting given its velocity and shear force

B. <u>Methods of Particle Entrainment</u>:

Fluid Shear Force > (Force of Friction + Force of Gravity)

1. <u>Fluid "lift force"</u>: "airfoil" fluid principle in which fluid flow above a particle creates a low pressure zone, allowing particles to lift vertically and overcome force of gravity (Bernoulli Effect)

a. Wind/Air can lift particles up to medium sand

b. "Lift Force" becomes negligible as particle height = 0.5 diameter

c. Fluid Viscosity can further entrain particles through advective shear transport.

d. Pressure aboe is less than pressure below = net lift

2. Fluid Impact: Direct water-particle impact and particle mobilization

3. Turbulent Support: Upward flow component of turbulent eddies may provide a source of energy for particle entrainment. As Upward Flow Force > Force of Gravity (i.e. "force of settling"), the particles will remain in suspension

4. Grain-Grain Impact ("dispersive force")

C. Mechanical Transport Mechanisms

1. Suspension: fluid currents transport sediments within the main body of flow (primarily fine sand, silt and clay under normal ranges of water viscosity) (Driving Force: Turbulent Flow Conditions, eddy transport)

2. Traction: "Bed Load" - transport concentrated at the basal flow boundary under the "drag force" of fluid shear.

(1) Saltation: bouncing of particles via upcurrents, and trajectory fall under force of gravity.

(2) Surface Creep: The forward movement of particles resulting from collisions with saltating particles.

In general, > particle diameter, > force necessary to mobilize particle, given equal particle diameter: > viscosity, < force necessary to mobilize particle.

VI. River/Stream Channel Morphology

A. Channel Morphology

1. Shape of river channel
   a. Plan View
      (1) Straight
      (2) Meandering
      (3) Braided
      (4) Anastomosed

   b. Cross-sectional View
      (1) width-to-depth ratio

2. Sinuosity of River Channel
   a. Magnitude and degree of bends in the river course

   b. Sinuosity Index: quantitative measurement of twisting of river course

      (1) $S = \frac{\text{absolute stream length}}{\text{valley length}}$ or $\frac{\text{thalweg length}}{\text{valley length}}$

(a) Thalweg = line connecting deepest points of river course

B. Meandering Streams
1. Basic Processes
a. Characterized by high-sinuosity, large single channel fluvial systems

b. Finer sediment load and lower gradient as compared to braided fluvial
(1) Meandering Fluvial Systems tend to be fine-load/suspended load (silt and clay) dominated rivers
c. Meandering channels migrate across large floodplain resulting in distinctive deposits
(1) Coarser cross-bedded channel sandstones
(2) Finer silt and mud-dominated "overbank" or floodplain deposits
(3) **Meandering systems tend to be dominated by suspended load

d. Morphological elements of meandering river system include:
(1) meander loops
(2) point bar sedimentation
(3) cut-bank erosion
(4) levee sedimentation
(5) oxbow lake sedimentation
(6) floodplain sedimentation

e. Meandering channel migrates across floodplain
(1) leaving coarse channel and pointbar deposits in its wake
(a) "ALLUVIUM": stream deposited debris.

f. Flood-stage processes (i.e. catastrophic events)

(1) move greatest volume of sediment and result in greatest morphological changes

(2) Crevasse splay: breaching of river channel banks with sand/sediment laden water spilling onto floodplain

(3) Overbank deposits:
(a) fine mud and silt deposited during recession of flood water

2. Meander Wavelength

a. Wavelength (L) of meander system directly proportional to discharge of system
(1) i.e. as Q >, L > and vice versa
(a) large Q rivers = larger meanders
(b) small Q rivers = small meanders

3. Meandering Process
   a. Centrifugal Force
      (1) Water flow in channel with mass of water thrown towards outside edges of bends
      (2) Momentum + Centrifugal Force result in higher velocity and shear force to occur on outside of river bends
         (a) Net Result = erosion and lateral meander migration on outside of channels

   b. Helicoidal Flow
      (1) Lateral components of flow vector are such that surface water is thrown to outside of meander bend and forced downward along the channel floor to the inside of the bend
         (a) net result = helicoidal flow = cork-screw/spiral flow around meander bends

   c. Cut Bank/Point Bar Process: Meander Migration

      (1) Cut Bank = erosive bank cut on outside of meander bend (owing to centrifugal force and increased velocity)
      (2) Point Bar: sediment carried from cut bank erosion is transported to the next river bend.

         (a) Point Bar = deposition on inside of meander bend in response to reduced velocity conditions

   d. Meander Cutoff

      (1) Extensive meander looping + cutbank erosion = river cutting off itself and meander loop
         (a) result: stranding meander loop and forming oxbow lake

C. Braided Streams
   1. Basic Processes
      a. Characterized by braided network of low-sinuosity channels separated by mid-channel sediment bars or islands.
         (1) Commonly bed-load dominated (sand and gravel) rivers

      b. Commonly found in
         (1) Glacial outwash plains
         (2) Distal reaches of alluvial fans
         (3) Mountainous drainage systems

      c. Associated with:
         (1) low vegetative cover, high runoff
         (2) high rate of sediment supply

2. Depositional Processes
  a. Sand to gravel dominated sediment transport
  b. bedload transportation dominant
  c. Rapid shifting of migrating sediment bars
  d. High-gradient, bedload dominated, low-sinuosity river system

    (1) Braided Rivers = higher gradient as compared to meandering rivers

3. Sinuosity

  a. Braided Rivers characterized by low-sinuosity form
  b. Coarse sand and gravel = low relative cohesion compared to fine silt and clay

    (1) much more easily eroded channel walls
    (2) Wide, shallow channels tend to develop

D. Anastomosed Channels

1. Hybrid morphologic form: a cross between meandering and braided morphologies
  a. Multiple channel system analogous to braided, however
  b. Low-gradient, narrow, deep channels with stable banks
    (1) common in high vegetation ecosystems where vegetative bank stabilization is prevalent

VII. Equilibrium Concepts and the River System

A. The Graded Equilibrium Model

1. Base level: an imaginary surface of streamflow equilibrium, approximated by sea level. For the most part, the ultimate destination of fluvial drainage is the sea, which forms a surface, below which deposition takes place, above which erosion takes place, and at which transportation only takes place.

  a. Inland base level: maintains a gentle gradient to allow water drainage
  b. Ultimate base level: sea level.

2. Local or temporary base level: inland equilibrium surfaces (not at sea level), that form lower limits of downcutting because of specific structural, geologic, or drainage conditions.

  a. e.g. a local base level is formed by the confluence of a lower order stream with a higher order one, a lower order stream can not cut lower than its downstream higher order cousin

b. Impoundments or lakes form temporary base levels for local stream drainages.

3. Stream Equilibrium Model: A "graded" stream is one in which the longitudinal gradient of the stream has become modified through the erosion/deposition process such that equilibrated-transport is the only process occurring.

a. Graded Stream: equilibrium between energy, velocity and load available for transport.

(1) Ideal Graded Stream: a purely transportational system with no erosion or deposition, transport from head to mouth of stream

4. Controlling Factors of Equilibrium System

a. Slope/Gradient

(1) graded slope:
- (a) concave up
- (b) steepest gradient at head
- (c) gently flattening gradient to mouth

(2) Slope Adjustment
- (a) fluvial adjustment of slope in response to changes in sediment load
- (b) > slope, > velocity, > carrying capacity

(3) Local and regional base level changes will result in adjustment of slope
- (a) local change = damming of river
- (b) regional change = sea level rise/fall

b. Discharge

(1) Discharge influences Velocity
- (a) Q >, V>

(2) As Q>, V>, sediment carrying capacity increases
- (a) Net result: erosion-----lowering of gradient

(3) As Q<, V<, sediment capacity decreases
- (a) Net result: deposition----steepening of gradient

(4) Short Term vs. Long Term Changes in Discharge
- (a) Seasonally vs. Climatically controlled

c. Sediment Load

(1) Sediment Load and Supply function of...
- (a) climate/weathering
- (b) vegetative cover
- (c) bedrock geology/structure

(2) Load as a controlling Factor

(a) If Load > (i.e. volume and grain size), deposition occurs, > slope, > velocity, > carrying capacity of stream to equilibrium

(b) vice-versa for decreasing load

(3) Down-gradient Relationships

(a) decreased gradient

(b) decreased grain size

i) abrasion and grain breakdown

(c) increased discharge

i) increased discharge + decreased grain size = excess velocity, result in downcutting to form lower gradient

Relationship Summary:

Action	Response	Slope
Increase in Load	Aggradation	Increases
Decrease in Load	Degradation	Decrease
Increase in Discharge	Degradation	Decrease
Decrease in Discharge	Aggradation	Increase

Degradation = erosion and downcutting
Aggradation = long-term accumulation of sediments

5. Base Level and River Equilibrium

a. Rise Base Level ------ Aggradation of River Upstream

b. Lowering Base Level ------- Degradation and Downcutting

B. Valley Deepening or "Entrenchment" (Degradation)

1. Downcutting Process: wherever a stream possesses a high velocity or a large volume flow, a stream will expend most of its energy downcutting the valley.

a. process most effective in upstream portions where the gradient is steep and the valley narrow.

Result: Classic V-Shaped Cross-Sectional Profile of River Valleys

b. features in downcut valleys include: waterfalls, rapids, and cascades.

1) Knickpoints: abrupt, steep irregularities in a stream profile, perhaps due to resistance characteristics of bedrock

c. Terrace Development: vertical erosion results in abandonment of floodplains

Terrace = abandoned / elevated floodplain

Paired Terraces = terraces of equal elevation on both sides of valley

Strath Terrace = erosional terrace cut into bedrock, with thin alluvial veneer

Fill Terrace = depositional terrace = valley fill + incision cycle

c. Headward Erosion: backcutting and grading of stream profile occurs in a headward direction, with upstream erosion and retreat of knickpoints.

VIII. Drainage Patterns

A. Drainage Patterns Controlled By:
1. Slope of Land
2. Random Headward Erosion
3. Selective Headward Erosion
    a. Preferred Paths along Geologic Weakness of Underlying Framework
        (1) Lithologic/Mineralogic Weakness (preferred path of erosion)
            (a) Lithology and resistance to weathering and erosion

        (2) Structural Weakness (preferred path of erosion)
            (a) Joints, faults, bedding planes

**Streams/Rivers will find path of least resistance and minimum energy/work in relation to gravity; these paths of least resistance are often geologically/structurally controlled within the bedrock framework of the landscape

B. Drainage Patterns: Plan view geometric pattern of tributary network of drainage system. Often strongly controlled by underlying geology/structural relationships.

1. Dendritic- branch-like or leaf-like pattern with random merging of streams at acute angles.

    a. Most common pattern
    b. commonly associated with relatively homogenous underlying geology
        (1) horizontal sedimentary rocks or homogenous igneous rocks
        (2) Little to no zones of weakness in rock

    c. Consequent development

2. Trellis Pattern- parallel streams with elongated valleys connected to trunk drainage at high angles.

    a. Commonly found in fold belts with alternating layers of erosionally soft and resistant rock
    b. Subsequent development
3. Rectangular Pattern- pattern formed by right angle intersections of tributaries

a. Common in faulted/jointed terrane
   (1) igneous or sedimentary
   (2) May be used to characterize structural geology of region
b. Subsequent development

4. Radial Pattern - radially away from center high point
   a. E.g. volcano
   b. Consequent development

5. Centripetal - opposite of radial, merging of streams in a bowl-shaped depression.
   a. Structural/closed topographic basins
      (1) Basin and Range
   b. Karst terranes/sinkholes
   c. consequent Development

6. Annular- a cross between trellis and radial, where drainage follows alternating layers of resistant and non-resistant rocks found in a structural dome or basin.
   a. Circular/parallel drainage patterns
   b. Subsequent Development

IX. Stream Terraces and Erosion Surfaces

1. Stream and/or river terraces- planar surfaces of erosion, remnants former valley floors, that now stand above (in elevation) active stream channels and their flood plains

   a. elevated surfaces of erosion

   b. Implies that active stream/river channels have incised and/or downcut to deeper levels of erosion, stranding erosional terraces at higher elevations

      (1) Causes of Stream/River Downcutting
         (a) base level; eustatic sea level change
            i) lowering global sea level creates down-cutting in channel to re-establish a graded (equilibrium) profile tapered to base level

         (b) Tectonic Uplift of land area
            i) increases gradient of drainage
            ii) elevates stream channels above base level, resulting in down-cutting

         (c) Climatic Excursions
            i) Increased discharge --- increased velocity/shear force---- increased erosion and downcutting

2. Types of River Terraces

   a. "Strath" or "Cut-in-bedrock" Terraces (comprised of bedrock, erosional in origin)
      (1) erosional surfaces cut by river through lateral planation
      (2) surfaces cut into bedrock with thin veneer of gravel cover

   b. Fill Terraces (comprised of alluvium)
      (1) Valley fill sequence (depositional in origin)
         (a) aggraded depositional sequence
            i) original valley downcutting, followed by aggradation, followed by renewed downcutting and surface abandonment

   c. Cut In Fill Terraces (comprised of alluvium, erosional in origin)
      (1) Valley-Fill + erosion sequence
         (a) original valley downcutting (erosion)
         (b) aggradation of alluvial fill (deposition)
         (c) renewed lateral planation of floodplain (floodplain erosion)
         (d) renewed vertical downcutting and abandonment

   d. Nested Fill Terraces

3. Correlation of Terraces

   a. Detailed surveying with cross-sections
      (1) matching of accordant relief, grade and elevations
   b. Correlation of Soils Chronosequences developed on surfaces
   c. Correlation of numerical age dates (e.g. C 14 dating of wood/charcoal)

4. Other Erosion Surfaces

   a. Stripped/eroded structural surfaces
      (1) dip-plane erosion
         (a) controlled by differences in lithologic resistance to erosion
   b. Marine erosion surfaces
      (1) sea terraces
         (a) derived from wave-base erosion along beach areas
         (b) subsequent uplift/sea level drop with surface abandonment

X. Paleohydaulic Methods

A. Critical Question: What is the flood history of a river beyond the recorded data record?

1. Why - to examine the extreme flood events in the context of landuse planning and floodplain management.

2. Problem - river gage / discharge records only extend back to 100 years or less. What about all the other floods not recorded?

B. Tool kit for the paleohydrologist

1. Ecosystem Response to Flooding
   a. Vegetation adjacent to floodplain
   b. Species adjustment to flood frequency
      (1) "Disturbance Regime"

   c. Individual organism records
      (1) Tree rings, scars, sycamore tipping etc.

2. Slackwater Deposit Analysis ("bathtub rings of sediment / deposits")

   a. Slackwater = quiet flood waters
      (1) fine-grained sedimentation (sand, silt, clay)

   b. Locations for Slackwater Record
      (1) Side Tributaries
      (2) Caves
      (3) Floodplains

3. Tractive load size (Grain Size Analysis - what moved when?)
   a. How to determine what moved.
      (1) flake scars bruises on sheletered surfaces,
      (2) multiple impact marks,
      (3) Fe staining (Cheat),
      (4) imbricated w/ tires, plastics, lumber, etc.,
      (5) aerial photography
      (6) BFR Analysis:
         (a) BFR = Big F.... Rocks, how did they get there, what was the hydraulic regime?

b. Grain-Size / Hydraulic Equations - What equations can one plug into?

$T_c = 166\ d$	
$D = 0.0001\ A^{1.21}\ S^{-0.57}$	(Knox, 1987)
$V = 0.065\ d^{0.5}$	(Williams, 1983)
$V_c = 0.18\ d^{0.44}$	(Koster, 1978)
$V_c = 0.18\ d^{0.49}$	(Costa, 1983)
$Q_{1.5} = 0.011\ L_m^{1.54}$	(Williams, 1983)
$8_m = 166\ Q_m^{0.46}$	(Carlston, 1965)
$T = 0.030\ d^{1.49}$	(Williams, 1983)
$T = 0.17\ d$	(Williams, 1983)
$T = 0.079\ d^{1.29}$	(Williams, 1983)

Symbols (Williams, 1984)

A = intermediate axis of largest clasts, mm
d = particle diameter, mm
D = competent flow depth, m
8_m = meander wavelength, m
$Q_{1.5}$ = discharge of 1.5 yr flood, m^3/s
Q_m = mean annual discharge, m^3/s
S = energy slope (approx. = topo. gradient), m/m
V = mean flow velocity, m/s
V_c = threshold (critical) flow velocity, m/s
T_c = threshold (critical) tractive force, N/m
T = bed shear stress, N/m
T = stream power/m of width, watts/m^2