Introduction to Hydrology

I. Introduction

A. Hydrology - study of water

1. Spatial and temporal variations of water mass
    a. mass displacement / water circulation
    b. spatial distribution
        (1) global
        (2) regional
        (3) local watershed
    c. Temporal distribution
        (1) hours, days, weeks, years, millions of years

2. Physical and chemical processes that affect spatial and temporal variations

3. Physical Systems Analysis
    a. Mass and Energy
    b. Mass-Energy Flux (mobilization of mass and energy)

B. Hydrologic System

1. Water storage compartments ("Mass storage")
    a. Atmosphere
        (1) water vapor
            (a) gas phase ("humidity")
        (2) water condensate
            (a) clouds / precipitation
            (b) "weather" systems
    b. Oceans
    c. Continental Areas
        (1) Lakes
        (2) Rivers
        (3) Glaciers
        (4) Groundwater

2. Water Transfer Functions (Energy-Mass Interaction)
    a. Evaporation (surface water to atmosphere transfer)
        (1) triggering mechanism = heat gain
        (2) energy source = solar

    b. Precipitation (atmosphere to surface transfer)
        (1) triggering mechanism = heat loss
        (2) energy source = solar / gravity

    c. runoff (channelized flow / overland flow)
        (1) energy source = gravity

d. infiltration (surface to groundwater transfer)
  (1) energy source = gravity

e. transpiration (surface - vegetation exchange)
  (1) energy source = solar / photosynthesis

C. Temporal and Spatial Scales in Hydrology

1. Temporal
  a. Thunderstorms ~minutes to hours
  b. Floods ~ days to weeks
  c. Runoff Cycle ~ decades to centuries
  d. Shallow groundwater circulation ~1000's to 10,000's years
  e. Development of Major River Basins ~ 100,000's to millions of years

2. Spatial
  a. thunderstorms ~ 1 km
  b. groundwater / aquifer systems ~ 10's of km
  c. major river basins ~1000's to 10,000's km

D. Variability of Hydrologic Processes

1. Highly variable over space and time
  a. e.g. Oregon climate transect from Coast to Coast Range to Interior

2. Deterministic vs. Stochastic Processes
  a. Deterministic - predictable hydrologic patterns
    (1) e.g. weather forecasts
      (a) deterministic on short term
      (b) seasonal predictions / probability

  b. Stochastic - random hydrologic patterns

3. Statistical Approaches to Hydrologic Data Collection and Analysis

  a. Data limited in space and time
    (1) e.g. discreet sampling stations at discreet times

  b. Interpolation between time / space data points
    (1) statistical analysis and probability

II. Significance of Water

A. Essential for animal and plant life to exist, forms the medium in which biochemistry can take place.

B. Water solutions transport nutrients and elements to organic tissues, nourishing them. Carries waste products out of tissues.

1. Mass of living organisms comprised of water ranges from 65-95%

C. Surface water covers more than 70% of the Earth's surface ("The Blue Planet")

D. Hydrologic Cycle

1. The Earth as an Isolated System
   a. water mass is constant on the Earth
   b. energy may be transferred into / out of the system
      (1) e.g. solar energy / heating of atmosphere

2. Water mass and energy may be transferred from one storage compartment to another.

III. THE HYDROLOGIC CYCLE

A. General Statement: 99% of all earth's water is held in storage in form of oceans, lakes, glacial ice or groundwater.

1. The remaining 1% is involved in the continuous sequence of movement and change in the form of atmospheric moisture, precipitation, and subsequent runoff and drainage, perhaps temporarily stored en route.

B. The Hydrologic Cycle: a circuit of water movement, with storage areas interconnected by various transfer processes... water moves not only geographically, but through physical states as well.

1. Basic Model: Ocean Water----sun's energy---- evaporation -----atmospheric moisture----- condensation/precipitation------land/continental waters-----downgradient flow due to gravity------ back to ocean------and cycling through.

2. Surface to Air: Evaporation prime mechanism for transfer to atmospheric moisture.

   a. Ocean Evaporation- heat and wind operate on oceans and result in evaporation of water from liquid to vapor form (especially effective in lower latitudes, areas with most direct heating from sun's rays)

   b. Land Evapotranspiration- water is not only release to the atmosphere on land through evaporation, but also through transpiration of water vapor from plants/trees to the atmosphere.

   c. Water Vapor Movement:
      (1) Convection- vertical movement of moisturelaiden air masses through heat transferprocess

(2) Advection - horizontal transport of airmasses by wind currents.

3. Air to Surface: atmospheric water vapor is eventually condensed into liquid or sublimated into ice to form cloud particles = precipitation

4. Surface and Ground Waters: precipitation on land can run several possible courses:
   - a. accumulation/ponding on the continental surfaces (will subsequently be subject to high rates of evaporation).
   - b. surface runoff: in form of streams and rivers, eventually being subject to partial evaporation and final emptying back to sea.
   - c. Infiltration into the ground and uppermost strata comprising the lithosphere; forming "ground water"
   - d. Vegetative interception: the interception of precipitation by the vegetative canopy of the biosphere, may be subject to evaporation or eventually fall to ground.

5. Duration of Cycle: water may become temporarily stored and removed from the cycle from hours to days, to years to 100's of thousands of years...depending on the geohydrologic circumstance.

C. Moisture Inventory:
1. Oceans: contain 97% of Earth's water
   - a. >70% of Earth's Surface Covered in Water
2. Glaciers: 2% of all moisture, comprising 75% of worlds fresh water
   - a. Continental Ice Sheets
     - (1) Antarctica
     - (2) Greenland
   - b. Ocean Ice
     - (1) Antarctic Shelf
     - (2) Arctic Sea
   - c. Glaciers = Savings Account of Fresh Water
   - d. Ice-Sea Water Budget
     - (1) Glacial Climates
       - (a) < Ocean Volume
       - (b) > Ice Volume
     - (2) Interglacial Climates
       - (a) > Ocean Volume
       - (b) < Ice Volume
3. Ground water: 0.5% of total
   - a. Surface Transfer
     - (1) Springs
     - (2) Anthropogenic Transfer
4. Fresh Surface Water: 0.2%
   - a. Lakes, Rivers
5. Soil Moisture: 0.1%
6. Atmospheric Moisture: 0.0001%
7. Biological Water: negligible

II. Physical and Chemical Properties of Water

A. Can exist in all three physical states: liquid, solid (ice), and gas (water vapor)

B. Transformation Processes related to energy input and entropy of water: heating of water, > atomic activity of the water molecules, i.e. > vibrational energy of water atoms.

1. ICE ----------HEAT----- WATER-------HEAT -------WATER VAPOR
   (<32 degrees) (32-212) (>212 degrees F)

C. Water is one of few earth substances that remains in a liquid state at the operating surface temperatures of the earth.

1. The liquidity of water makes it a dominant and pervasive component of all earth processes

D. Water has High Heat Capacity- it has a capacity to absorb and hold energy with only a small amount of temperature rise.

1. important for water-based organisms to regulate temperature
2. produces the moderating effects of oceans on climate
   a. oceans = warm residual heat in winter (warms air temp.)
   b. oceans = slow rate of heating in summer (cools air temp.)

E. Water expands in volume when it freezes/ becomes colder, in contrast to majority of substances (which contract when colder)

1. Result Density of ice < Density of water: thus ice floats on water
2. The crystal structure of ice is a hexagonal arrangement of water molecules
   a. creates increased volume and decrease in density
3. importance: lakes and oceans freeze from top down, life would not be possible if ice was more dense than water (i.e. freezing from bottom to top).

F. Water strongly influenced by the force of gravity, constantly driven downward, and can possess great erosive/ landscape carving force

G. Water has property of high surface tension, ability to have strong molecular attractive forces (sticks to itself and electrostatically attracts ionic forms of elements)

1. surface tension - dipolar molecules and hydrogen bonds result in surface tension on top of water mass

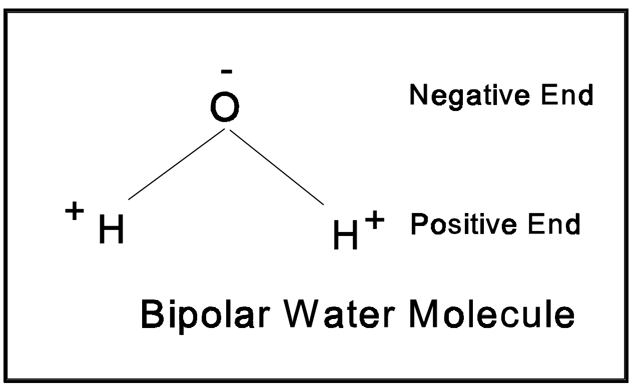
a. surface tension = intermolecular force
b. water surface may support masses of materials

2. Capillarity- phenomena of water moving upward against the force of gravity, due to strong electrostatic adhesive forces, most notable in narrow, restricted pore spaces where surface to surface contact in high.

H. Water acts as a "universal solvent" and can dissolve most any substance over time. Water + carbon dioxide forms a mild carbonic acid solution naturally in hydrosphere, as an acid can result in cationic exchange with positive ionic species, and result in chemical breakdown of substances.

1. Bipolar Water Molecule H_2O

2. Covalent bonds between hydrogen and oxygen (strong bond, via sharing of electrons)
a. Hydrogen: 1 valence electron (atomic no. of 1)
b. Oxygen: 6 valence electrons (atomic no. of 8)



3. Hydrogen bonds- given a mass of water molecules, the opposite ends will attract molecularly, forming weak hydrogen bonds

a. hydrogen bond between molecules is weaker than covalent within molecules
(1) water mass is fluid, but molecules are difficult to dissociate
(2) the weak hydrogen bonds between molecules allow water flow

b. Frozen state - water mass is defined by solid, rigid crystalline structure

(1) molecular vibrational energy decreases to the point where the hydrogen bonds lock the molecules into a crystalline structure
(2) hexagonal crystal lattice with increased volume
(3) freezing point at 32 F (0C) for pure water, but supercooling of water is possible in impurities are present (dissolved salt, suspended solids)

c. Evaporation - molecular vibrational energy increases, breaks hydrogen bonds between molecules, individual molecules are liberated from water mass
(1) evaporation at air-sea interface is at temp. < boiling point

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Overview of Physical Properties of Water

A. Temperature-Density-Viscosity Relations

Temp. (C)	Density (gm/cm3)	Viscosity (centipoises)
5	0.999965	1.5188
10	0.997000	1.3097
15	0.999099	1.1447
20	0.998203	1.0087
25	0.997044	0.8949
30	0.995646	0.8004
35	0.99403	0.7208
100	0.95865	

Note: viscosity is the measure of a fluid's resistance to flow. The higher the viscosity (e.g. molasses), the more sticky and resistant to flow the fluid is.

B. Weight Density of Water

at 40 F, weight density = 62.4 lb/ft^3 (1 ft^3 = 7.48 gallons)
at 200 F, weight density = 60.135 lb/ft^3

C. Boiling Points of Water vs. Elevation (atmospheric pressure)

Elevation (ft)	Boiling Point (F)
-1000	213.8
0	121
5000	202.9
10,000	193.7

Watershed Fundamentals

INTRODUCTION

Making decisions about a watershed is an important responsibility; decisions must be based on a solid understanding of the characteristics of the watershed and how physical processes shape watershed conditions. This section provides basic background information on watershed functions and processes to help users understand the assessment procedure and the results of the assessment process. Watershed "processes" refer to those natural physical, chemical, and biological mechanisms that interact to form aquatic ecosystems. For example, the input and routing of water, ***sediments***,[1] and large wood through stream channels involve many inter-related processes occurring both in-channel and upslope.

WHAT IS A WATERSHED?

The term "watershed" describes an area of land that drains downslope to the lowest point (Figure 1). The water moves by means of a network of drainage pathways that may be underground or on the surface. Generally, these pathways converge into a stream and river system that becomes progressively larger as the water moves downstream. However, in some arid regions, the water drains to a central depression such as a lake or marsh with no surface-water exit.

Watersheds can be large or small. Every stream, tributary, or river has an associated watershed, and small watersheds aggregate together to become larger watersheds. It is a relatively easy task to delineate watershed boundaries using a topographical map that shows stream channels. The watershed boundaries will follow the major ridge-line around the channels and meet at the bottom where the water flows out of the watershed, commonly referred to as the mouth of the stream or river.

Figure 1. Watershed is an area of land that drains downslope to the lowest point.

The ***connectivity*** of the stream system is the primary reason why aquatic assessments need to be done at the watershed level. Connectivity refers to the physical connection between tributaries and the river, between surface water and groundwater, and between wetlands and these water sources. Because the water moves downstream in a watershed, any activity that affects the water quality, quantity, or rate of

[1] Terms found in bold italic throughout the text are defined in the Glossary at the end of this component.

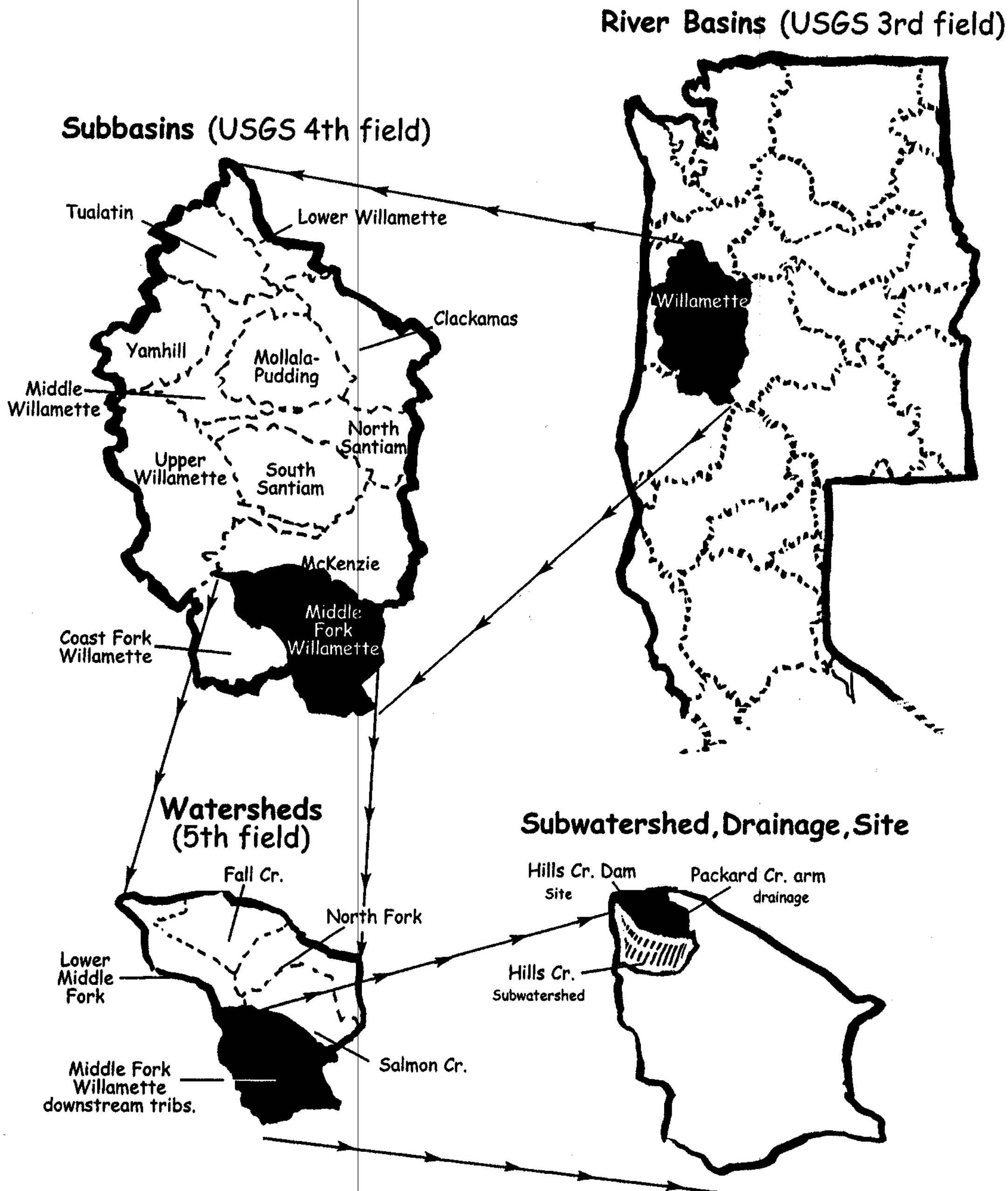


Figure 2. Suggested terminology for watershed descriptive terms based on USGS hydrologic "fields." These fields correspond to the following terms: river basin (3rd field), sub-basin (4th field), and watershed (5th field). In the figure, the Willamette River Basin is divided into sub-basins including the Middle Fork Willamette, which is divided into watersheds including the Middle Fork Willamette downstream tributaries. This watershed then includes a subwatershed, drainage, and site, as seen in the lower right of the figure.

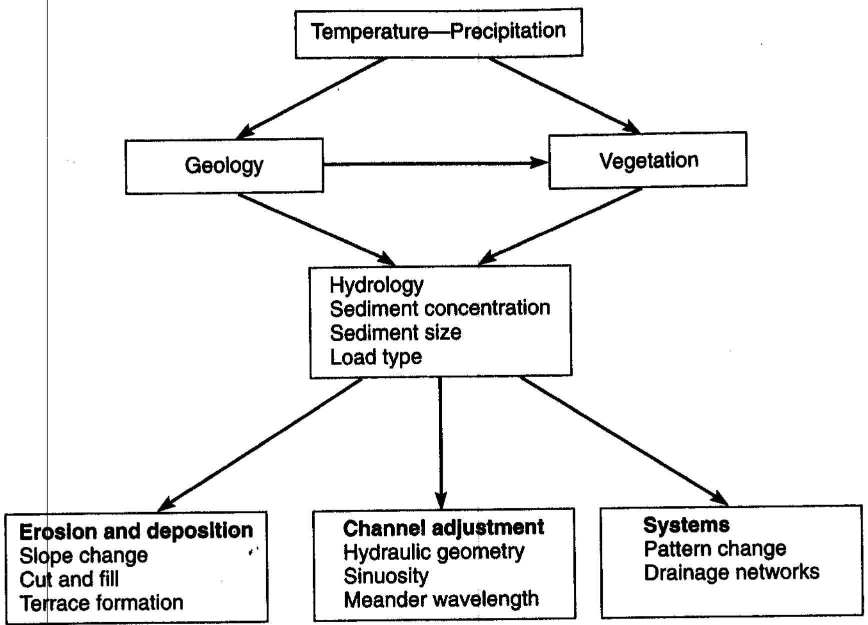


Figure 2.16
Hypothetical flow chart showing how climatic variables exert an influence on rivers. A change in climate alters sediment concentration, sediment size, or load type, requiring a response by the river system. Responses vary depending on local conditions.

much water and sediment get to a river channel. Variations in these two factors require threshold adjustments that can occur in a number of different ways (fig. 2.16). In addition, the lag in response is controlled by how rapidly a new vegetal screen and its characteristics can develop under a new climatic regime. This factor is not as straightforward as we would like. Predictions of response to possible future climate changes are clouded because vegetation biomes before the Holocene (ca. 10,000 years B.C.) have no modern analogs (Overpeck et al. 1992). This fact suggests that scientists cannot predict with certainty what types of vegetation communities will develop if our climate reverts back to conditions that were prevalent during the Pleistocene.

Another problem is that the same climatic change may prompt entirely different sediment yields and therefore different geomorphic responses. For example, considering figure 2.15 again, assume that a 15-cm decrease in precipitation occurs in a particular drainage basin that had an effective precipitation of 45 cm prior to the change. The reduced precipitation will result in a greatly increased sediment yield. However, the same 15-cm decrease in a basin having a 35-cm annual precipitation prior to the change will produce a major reduction in sediment yield. Theoretically, then, the same climate change may result in cutting by one river and filling by another because the type and amount of sediment yielded during adjustment to the new climate is oppositely affected. What this tells us is that the effect of climate change may be highly dependent on the antecedent values of temperature and precipitation. If that is a true statement, knowledge of preexisting climate may be as important in understanding how systems respond to climate changes as knowing the magnitude of the change itself.

In sum, the relationships among climate, process, and landform are not easily determined because the effect of change is sidetracked into ancillary factors. The adjustments of these factors in the new climate provide variable conditions of load and water that spur responses that are not predictable under the present state of our knowledge. Thus, we have not been able to describe clearcut relationships between climate and landforms because we are far from understanding the climatic geomorphology scheme.

SUMMARY

In this chapter we briefly examined climate and endogenic factors as major external controls on geomorphic systems. Endogenic influence occurs primarily through the addition of mass and energy by volcanism and tectonic activity. The most important tectonic processes are those producing vertical movements of the surface. One of these is the isostatic adjustment required when the internal mass balance is upset. Other vertical movements, associated with faulting and warping, are integral parts of a subdiscipline known as tectonic geomorphology, in which the relationships among tectonics, processes, and landforms are utilized in a variety of geologic and environmental studies. In most cases, vertical displacements induce threshold conditions and responses in the affected surficial systems.

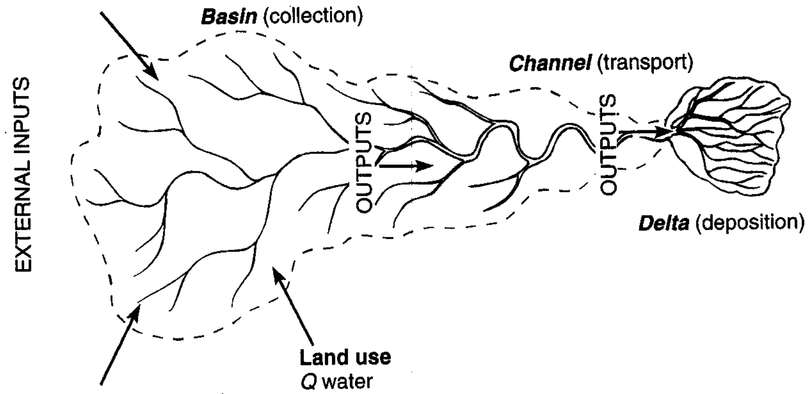


Figure 5.1B
Schematic surface components of the fluvial system. The tributaries provide links between lithology and climate and are adjusted to both. Channel characteristics vary in response to the external variables of sediment and water discharge (Q), which are influenced naturally from climate, tectonic, and lithologic factors. Human influence also modifies these variables through land use alterations.

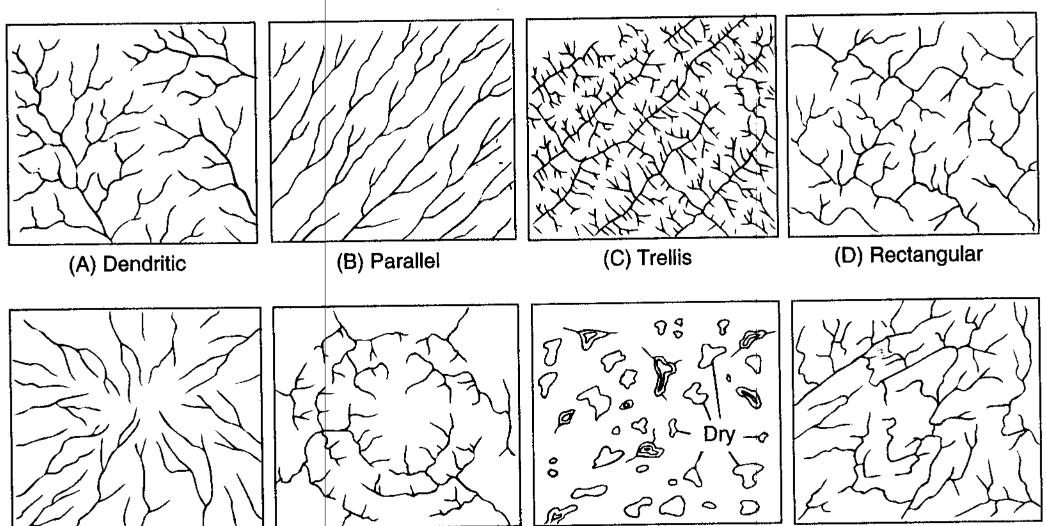


Figure 5.2A
Basic drainage patterns. Descriptions are given in table 5.1.
(Howard 1967, reprinted by permission)

underlying geology, described in figure 5.2A and table 5.1. Because the gross character of these patterns is evident on topographic maps and aerial photos, the patterns are useful for structural interpretation (fig. 5.2B) (Howard 1967) and for approximating lithology in a study of regional geology.

In a hydrologic sense, however, prior to World War II most basins were described in qualitative terms such as well-drained or poorly drained, or they were connoted descriptively in the Davisian scheme as youthful, mature, or old. The mechanics of how river channels or networks actually form and how water gets into a channel was poorly understood by geologists and hydrologists alike. This early twentieth-century view of streams and drainages contrasts markedly with the avant-garde approach presented by R. E. Horton during the latter part of this period (Horton 1933, 1945). His attempt to explain stream origins in mathematical terms and to describe basin hydrology as a function of statistical laws marked the birth of quantitative geomorphology. We now know that many of Horton's original ideas are only partially correct. Still, modern geomorphic analysis of drainage basins has its roots in Horton's original work, and his thinking has been instrumental in the development of modern geomorphology.

I. GROUNDWATER OCCURRENCE AND PROCESSES

A. Introduction

1. Water contained within cracks, fractures and pore spaces of soil, sediment and rocks beneath the surface of the earth

2. Groundwater is much more voluminous and ubiquitous than surface water, commonly found within 2500 feet depth below land surface.

3. Groundwater flow path: atmospheric precipitation percolates into soil/bedrock directly or from surface lakes and streams, and generally flows downward under the force of gravity until it reaches some sort of physical barrier or impermeable zone, which either severely impedes flow or stops it altogether.

4. Types of Groundwater

   a. Meteoric Water: water recently circulated from atmospheric cycle

   b. Connate Water: water that is entrapped with sediments when they are deposited, and subsequently gets buried and lithified with the sediments in form of sedimentary rock.

      (1) I.e. connate water = fossil water.

   c. Juvenile Water: water freshly derived from deep within the interior of the earth via volcanic processes.

B. Groundwater Hydraulic Mechanisms

1. <u>Porosity:</u> ratio, in per cent, of the volume of void space to the total volume of sediment or rock

$$P(\%) = \frac{\text{total volume - volume of solids}}{\text{total volume}} \times 100$$

   a. Porosity is the primary governing factor influencing the ability of rock or sediment to store fluids (e.g. groundwater or hydrocarbons)

   b. Types of Porous Openings

      (a) Intergranular Porosity = primary pore spaces present between particles of a sediment or rock deposit

(3) Porosity of Crystalline Plutonic and Metamorphic Rocks

(a) Very low primary porosity
(b) Secondary "structural porosity"
i) joints, fractures, faults -----porous zones
a) may achieve 5-10% on avg, up to 50% porosity in some instances

(4) Porosity of Volcanic Rock
(a) Vesicles and columnar jointing may create relatively high porosities

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

a. Permeability (K) is largely a function of:

(1) grain size, size of pore space
(2) shape of grains/shape of pore space
(3) degree of interconnected pore space

b. Darcy's Law

$$Q = \frac{KA(P_2-P_1)}{uL}$$ where,

Q = Volume Discharge Rate (cm^3/sec)
K = Permeability (millidarcy = mD)
A = Cross-sectional area at perpendicular to flow (cm^2)
L = length along which press. diff. is measured (cm)
(P_2-P_1)= pressure difference (atm) between two points separated by distance L
u = viscosity of fluid (centipoises)

Generally, well sorted sand and gravel display high porosity and permeability, however, a poor sorted sand with much matrix material will have a low permeability.

Unpacked clay, may have a very high porosity but very low permeability.

Generally clay/shale make for good permeability barriers, while sand and gravel readily transmit fluids. However secondary overprints such as structural deformation and diagenetic alteration (post-depositional changes in mineralogy) can drastically influence permeabiltiy and porosity.

2. Zone of Saturation: or phreatic zone: zone below zone of aeration, in which all pore spaces, fractures and cracks are filled or saturated with water. (i.e. groundwater).

   a. Water table: the top surface of the saturated zone, open to atmospheric pressure conditions via the vadose zone above.

   b. Ground water flow: groundwater flows along permeable zones under the force of gravity, taking the path of least resistance. Ground water flows along porous paths from areas of higher water table elevation to areas of lower water table elevation.

   c. Water table configuration: water table generally follows the surface topography of the land above, rising to higher elevations beneath hills, and lower elevations beneath valleys, generally water table deeper beneath hills, and coming closer to surface beneath valleys.

      (1) intersection of water table with surface of the earth results in surface flow of water in form of springs or seeps, or perhaps manifested as a lake or swamp.

   d. Pressure Relationships: the level of the water table is generally a surface of constant pressure or hydrologic head.

      (1) A well dug to intersect the water table, will fill with water to the level of the water table, unless under some kind of hydrostatic pressure (artesian conditions)

      (2) Groundwater Maps: elevations of top of water table can be mapped and contoured

         i) Ground water elevations derived from measuring water levels in wells

         ii) Hydraulic Gradient = rise/run or slope of water surface = (vertical difference/horizontal distance)

            a) Groundwater flow generally parallel to lines of gradient (i.e. perpendicular to contour lines in downgradient direction under force of gravity)

      (3) Cone of depression- if water is pumped from a well faster than it can be replaced, the level of the water table will be drawn down in the shape of an inverted cone.

D. Aquifer Types

1. Definitions

a. Aquifer: porous rock/sediment units that have a capacity to contain water, pores can be formed by openings between grains (primary porosity) or by cracks and fractures in the rocks (secondary porosity)

(1) Common Aquifers: unconsolidated sand and gravel, sandstone, dissolved/fractured limestone, lava flows, fractured crystalline rocks.

b. Aquiclude: Impermeable layers which will not transmit or store groundwater, tend to form the upper or lower boundaries of aquifers

c. Aquitard = "leaky" aquiclude: low permeability layers which transmit groundwater at very slow rates in both vertical and/or horizontal directions.
(1) More permeable than aquiclude

2. Unconfined Aquifers: aquifers in vertical and hydraulic continuity with land surface.

a. Water Table Aquifers = Unconfined Aquifers

(1) Water of saturated zone in open contact with atmopheric pressures

(2) Water percolates through vadose zone to phreatic zone

(3) Capillary Zone: layer immediately above water table where water moves upward under high surface tension and capillary forces

3. Confined Aquifers: aquifers that are separated from atmospheric pressures by impermeable zones or confing layers (water not referred to as "water table")

a. Confined aquifer and artesian conditions, relative to hydrostatic pressure

(1) Potentiometric surface: analogous to water table, but is elevation of water of confined aquifer that rises to equilibrium in open well penetrating confined aquifer

(a) may contour elevations to form potentiometric contour map
i) confined aquifer groundwater flow generally perpendicular to contour of potentiometric surface.

(b) confined aquifers commonly under hydrostatic pressure in response to rock compaction and pore fluid pressures

b. Artesian Aquifer: identified as water in a well that rises under pressure above the saturated confined aquifer horizon

(1) Conditions of formation:

(a) confined aquifer between two impermeable layers
(b) exposure of aquifer to allow recharge/infiltration
(c) hydraulic flux into the aquifer from water cycle

c. Free-flowing artesian aquifer

(1) Artesian aquifer in which pressures are such that water freely flows out onto the ground surface.

d. Perched Aquifers: localized zone of upper level groundwater occurrence "perched" above a laterally discontinous aquitard.
(1) forms a localized occurrence of groundwater above regional water table system (hybrid of confined and unconfined systems)

E. Groundwater and Environmental Concerns

1. Resource Development

a. Groundwater use for urban and domestic needs prevalent throughout North America
(1) Residential use in rural areas off "plumbing grid" of public water supplies
(2) Residential and Industrial use in arid and semi-arid portions of U.S.
(a) Groundwater useage very prevalent throughout the Mid-west and Far-west.

2. Environmental Hazards
a. Groundwater Contamination
(1) Industrial/Government Facilities
(2) Sewage/bacteria
(3) Mining
(4) Landfills

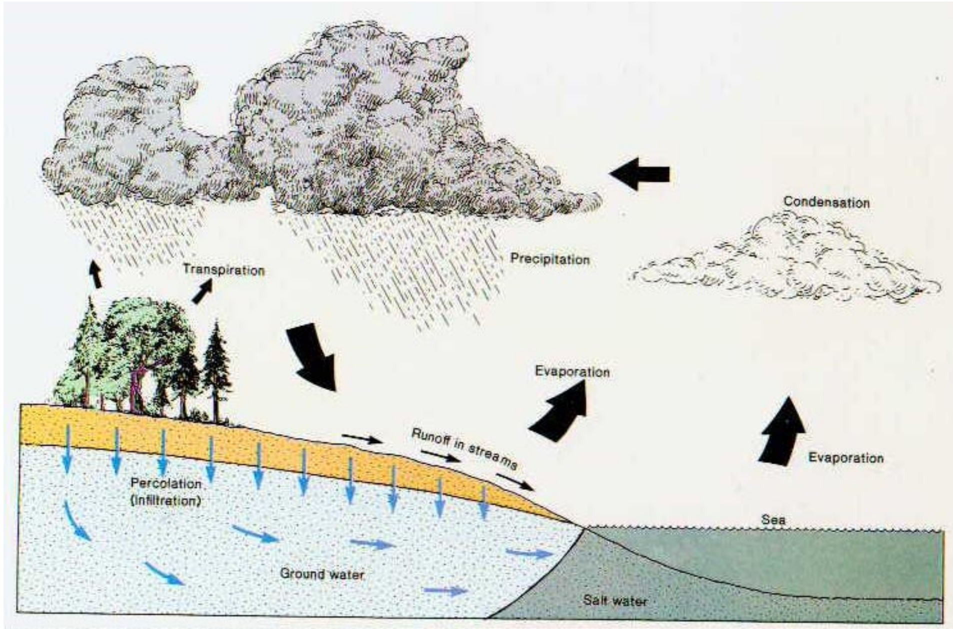
b. Ground Subsidence and Subsurface Fluid Withdrawal
(1) Extensive withdrawal of subsurface fluids
(a) groundwater
(b) Petroleum
(2) Fluid withdrawal results in decrease in pore pressure, leading to subsidence of land areas under lithostatic pressure

II. THERMAL SPRINGS AND GEYSERS

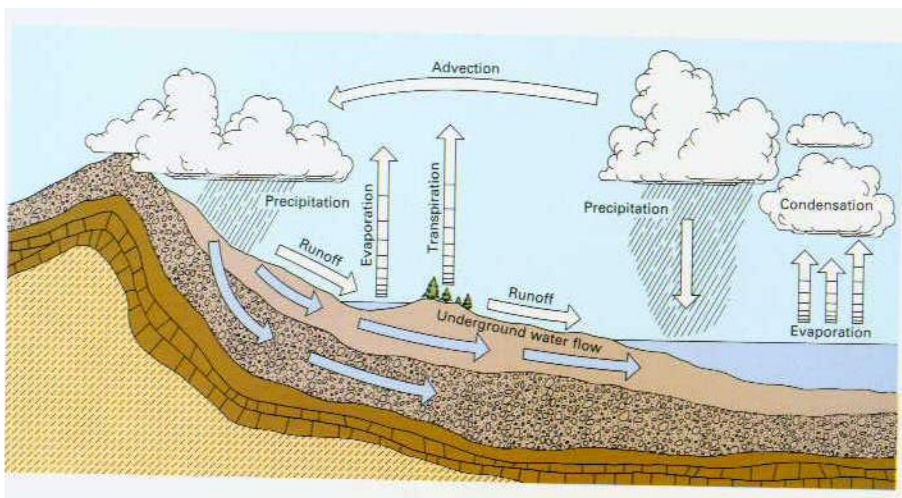
A. Hydrothermal Regions

1. Basically groundwater plumbing systems that circulate in portions of the earth's crust associated with high heat flow... water circulated and heated by earth's internal heat

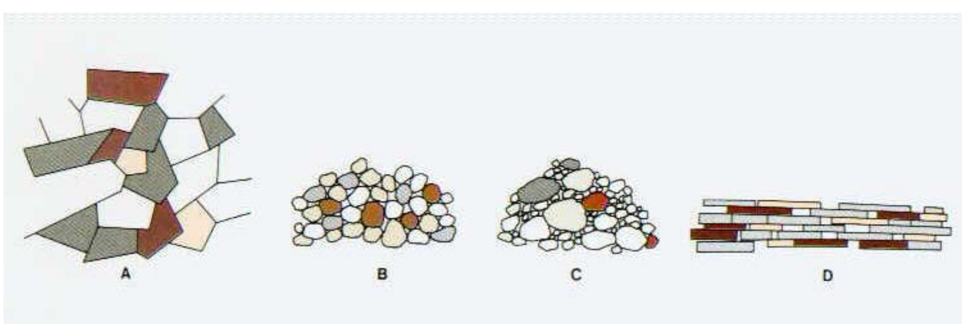
a. volcanic regions
(1) e.g. Yellowstone Park, WY
(2) Cascades / Eastern Oregon



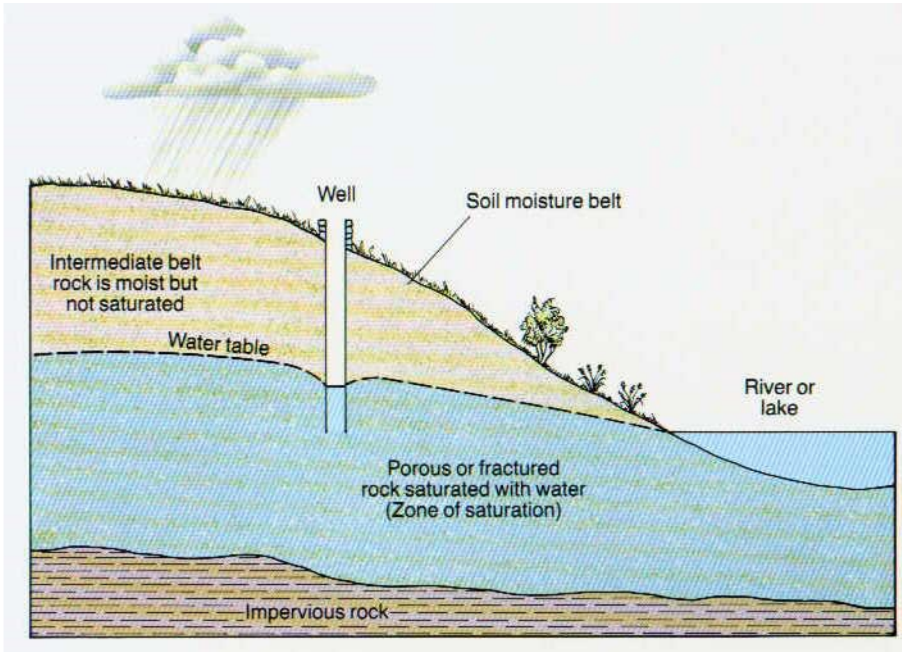
Water Cycle 1



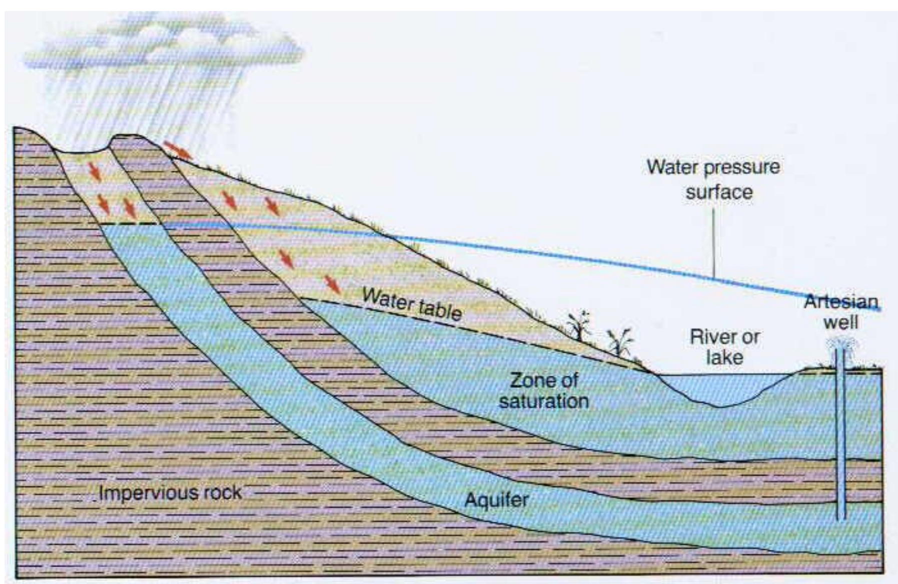
Water Cycle 2



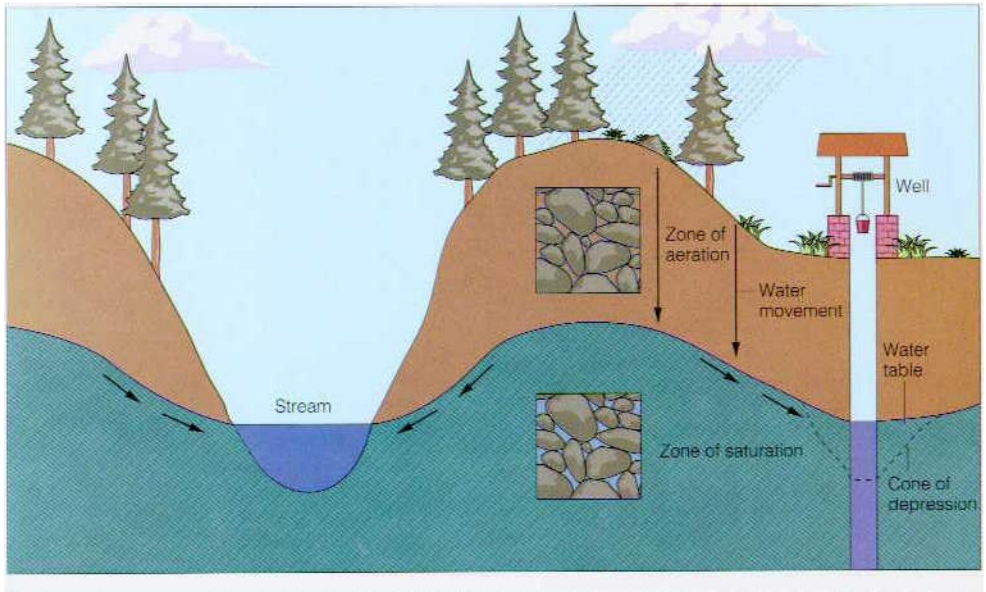
Degrees of Intergranular Porosity



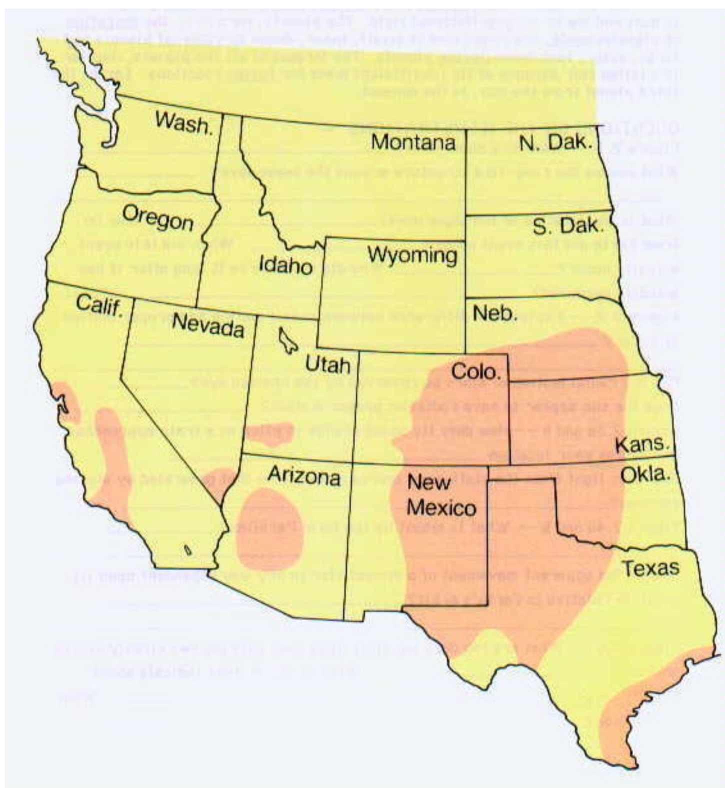
Unconfined Aquifer



Confined (Artesian) Aquifer



Well Dynamics in Unconfined Aquifer



Areas of Extensive Groundwater Withdrawal in Western U.S.