BASIC PRINCIPLES OF GROUND-WATER OCCURANCE AND FLOW

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Mike Wireman

Water well – Rural Romania

Water well – Castle in Austria
WHAT?
WHERE?
HOW?
BASIC PRINCIPLES OF GW OCCURRENCE AND FLOW

OUTLINE FOR THIS TALK

- WHAT IS GW?
- HYDROLOGIC CYCLE
- GEOLOGY AND GROUND WATER
- GW HYDROLOGY
- GROUND-WATER / SURFACE-WATER INTERACTION
- GROUND-WATER QUALITY
GROUND WATER

Subsurface water that occurs beneath the water table in geological sediments and formations that are fully saturated.

Subsurface water also occurs with-in near surface unsaturated sediments and formations above the water table. In the unsaturated zone voids are filled with air and water.
HOW GROUND WATER OCCURS IN ROCKS

The water table marks the top of the zone of saturation. Its level can rise or fall, depending upon the rate of water entering and leaving the ground.

Source: AIP6, 1983
Figure 8. Schematic diagram of the earth's water cycle—the hydrologic cycle.
## Estimated Water Balance of the World

<table>
<thead>
<tr>
<th>Hydrologic reservoir</th>
<th>Volume (%)</th>
<th>Residence time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans / seas</td>
<td>94</td>
<td>~ 4000 years</td>
</tr>
<tr>
<td>Ground water</td>
<td>4</td>
<td>2 weeks - 30,000 years</td>
</tr>
<tr>
<td>Glaciers / icecaps</td>
<td>2</td>
<td>10-1000 years</td>
</tr>
<tr>
<td>Lakes</td>
<td>&lt;0.01</td>
<td>~ 10 years</td>
</tr>
<tr>
<td>Wetlands</td>
<td>&lt;0.01</td>
<td>1-10 years</td>
</tr>
<tr>
<td>Rivers</td>
<td>&lt;0.01</td>
<td>~ 2 weeks</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>&lt;0.01</td>
<td>2 weeks - 1 year</td>
</tr>
</tbody>
</table>

Nice, 1971 (assumes equal distribution over entire surface of earth)
BASIC PRINCIPLES OF GW OCCURRENCE AND FLOW

OUTLINE FOR THIS TALK

- WHAT IS GW?
- GEOLOGY AND GROUND WATER
  - Geology of aquifers
  - GW regions, hydrogeologic settings, hydrostratigraphic units
- GW HYDROLOGY
- GROUND-WATER / SURFACE-WATER INTERACTION
- GROUND-WATER QUALITY
IMPORTANCE OF GEOLOGY

- GW OCCURS IN GEOLOGIC DEPOSITS AND FORMATIONS

- SUBSURFACE IS VERY HETEROGENEOUS

- LITHOLOGY / MINERALOGY OF GEOLOGIC MATERIALS GREATLY AFFECTS HYDRAULIC PROPERTIES AND GW QUALITY

- GEOLOGY CONTROLS TYPES OF AQUIFERS THAT OCCUR IN AN AREA

- AQUIFERS / HYDROSTRATIGRAPHIC UNITS
  
  Deposits and formations are grouped or split based on hydraulic characteristics—not lithology, fossils, age
AQUIFER

A geologic formation, part of a formation or group of formations that will yield significant quantities of water to a well.

An aquifer can store and transmit water easily.
GEOLOGIC MEDIA

UNCONSOLIDATED DEPOSITS vs CONSOLIDATED ROCKS

Sedimentary
  unconsolidated -- clays, silts, sands, gravels, cobbles
  consolidated -- shale, sandstone, siltstone, conglomerate, limestone

Igneous
  granites, basalts, diorites, monzonites, volcanic

Metamorphic
  quartzite, slate, marble
BASIC ELEMENTS

Sand and Gravel

Consolidated Rock

Carbonate Rock

Volcanic Rock

Hydrologically important rock types

**Major Aquifers**
- Gravel
- Sand
- Sandstone
- Limestone
- Basalt

**Aquicludes**
- Clay
- Shale

**Minor Aquifers**
- Till
- Conglomerate
- Siltstone
- Gneiss
- Quartzite
- Granite
- Marble
UNCONSOLIDATED DEPOSITS AND ROCKS AS AQUIFERS

- UNCONSOLIDATED FLUVIAL DEPOSITS
- INTERMONTANE VALLEY DEPOSITS
- COASTAL PLAIN DEPOSITS
- GLACIAL DEPOSITS
- SEDIMENTARY ROCKS
- IGNEOUS / METAMORPHIC ROCKS
Unconsolidated fluvial deposits

- Deposited by water
  - Streams
  - Lakes
  - Glaciers
  - Oceans

- Geometry /size of deposit depends on
  - Depositional setting
  - Source area and material
  - Time
Features also occur in consolidated sedimentary rocks.
Figure 3.6. Structure of a simple delta, shown in vertical section. The bottomset beds are deposited almost horizontally in front of the advancing foreset beds. Later, topset beds form on top of the foreset beds and represent a continuation of the landward alluvial plain. The topset beds truncate or cover the upper edges of the inclined foreset beds.

DRiscoll, 1986
INTERMONTANE VALLEY DEPOSITS

INTERMONTANE VALLEY:

- A basin like area between or within mountain ranges (also called a park)
- Formed by structural processes not by a river
- Contain thick sequences of unconsolidated and semi-consolidated alluvial/glacial/volcanic sediments
Often storage dominated
GLACIAL DEPOSITS

GLACIAL FLUVIAL DEPOSITS:
- ALLUVIUM
- OUTWASH

ICE CONTACT DEPOSITS:
- TILL

GENERALLY HYDRAULICALLY CONNECTED TO SURFACE WATER.
Figure 4.3 Schematic diagram of aquifer occurrence in the glaciated regions of the Midwest and Great Plains physiographic provinces.

(FREEZE, CHERRY, 1979)
CONSOLIDATED SEDIMENTARY ROCKS

- 70% OF ROCKS EXPOSED AT EARTHS SURFACE (OUTCROP / SUBCROP)
- SEDIMENTARY ROCK TYPES
  - 25% CONGLOMERATE
  - SANDSTONE
  - 25% CARBONATES
  - GYPSUM
  - 50% SHALE
  - SILTSTONE
  - CLAYSTONE
Basins contain oil/gas, coal, mineral and freshwater resources
How to manage development of combined resources
Minimize/mitigate environmental impacts
Sedimentary basins in Western USA commonly have thick carbonate and sandstone formations at depth (1000s of ft.) — which function as aquifers and aquifer systems. These aquifers extend over very large areas (1000s of mi²).

Significant meteoric (fresh) water at depth — focused recharge

Current research indicates significant permeability at depth — locally

Oil & Gas deposits in shallow & deep formations — gas occurs in deeper shale formations

Hydrogeology of deep GW is poorly understood due to:
- Limited use
- High cost to characterize & develop
CARBONATE AQUIFERS

<table>
<thead>
<tr>
<th>PRIMARY</th>
<th>POROSITY</th>
<th>HYDRAULIC COND.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clastic -</td>
<td>High</td>
<td>Mod</td>
</tr>
<tr>
<td>Precipitate-</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

SECONDARY POROSITY AND HYD. COND.

- Very important
- Solutional enlargement of fractures, joints and bedding planes
- Dissolution mechanisms favor development of larger openings
  - Higher $K$ in large openings
  - Water in smaller openings at saturation
- Highly anisotropic and non-homogenous
- Water table in carbonate aquifers
  - Be very flat due to high $K$
  - Be discontinuous
  - Be very deep in recharge areas
Figure 4.7  Schematic illustration of the occurrence of groundwater in carbonate rock in which secondary permeability occurs along enlarged fractures and bedding plane openings (after Walker, 1956; Davis and De Wiest, 1966).
IGNEOUS / METAMORPHIC ROCKS AS AQUIFERS

- Underlie 20% of land surface
- Fracture flow vs radial flow
- Volcanic rocks - extensive secondary permeability
Watershed management in fractured-rock settings
Figure 3.18. Stratigraphic relationship of deeply weathered igneous or metamorphic rock overlain by glacial drift. Clays are weathered from bedrock and collect on the surface as residual products.
Hierarchical Framework for GW Systems

**GW Regions** (15 Regions mapped by Heath, USGS)
- Geographic / physiographic areas where the compositions, arrangement and structure of the geologic formations that affect the occurrence and flow of ground water are similar

**Hydrogeologic settings**
- A composite description of all of the major geologic and hydrologic factors which control ground-water movement into, through and out of an area. It is a mappable unit with common hydrogeologic characteristics.
  - Not mapped for much of USA
  - A suite of hydrogeologic settings described for each gw region
Hierarchical Framework for GW Systems

- **Aquifer**
  A geologic formation, part of a formation or group of formations that will yield significant quantities of water to a well or spring

- **Aquifer zones**
  - Subdivisions of aquifers with different hydrologic conditions
    - Recharge area vs. discharge area
    - Confined vs. unconfined

- **Aquifer sites**
  - Specific features such as a spring, sinkhole, gaining reach of stream
Principle Aquifers – United States
Western Mountain Ranges GW Region
Hydrogeologic setting  Western Mountains Ranges GW Region
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- GROUND-WATER / SURFACE-WATER INTERACTION
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Q = KiA

Gradient = H/L = I (the energy required to move the water distance L)

Q = quantity of flow, gpd
A = cross sectional area of flow, ft²
K = hydraulic conductivity = gpd/ft²

Ft/ft
TOTAL HEAD = PRESSURE HEAD + ELEVATION HEAD
Vertical flow most often less than horizontal flow – but can be important in some hydrogeologic settings
Artesian
Water table /potentiometric surface maps should represent a single aquifer /flow system
MULTIPLE SCALE FLOW SYSTEMS

- Occur in hydrogeologic settings with complex topography and stratigraphy

- Vertical dimensions of flow systems
  - Local - 100s of meters
  - Intermediate - 100s - 1000s of meters
  - Regional 1000s of meters to kilometers
Storage coefficient / specific yield

The amount of water released per unit area of aquifer for a given unit head change

Confined aquifer – low sc
Unconfined – high sy
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GROUND-WATER / SURFACE-WATER INTERACTION

- Aquifer –stream interaction
- Hyphoreic zone
- Wetlands /fens
- Hillslope hydrology
- Springs
FIGURE 3.8  A. Cross section of a losing stream, which is typical of arid regions, where streams can recharge ground water. B. Cross section of a gaining stream, which is typical of humid regions, where ground water recharges streams.

FIGURE 3.9  A stream that is gaining during low-flow periods can temporarily become a losing stream during flood stage.
Gaining - losing relationship can vary temporally & spatially
FIGURE 3.3 Influence of the water-table gradient on baseflow. The stream in Part A is being fed by ground water with a low hydraulic gradient. A gentle rain does not produce overland flow, but infiltration raises the water table. The increased hydraulic gradient of Part B causes more baseflow to the stream, which is now deeper and has a greater discharge.

FETTER, 1988
Figure 4-18 Discharge and low flow indices of the Scioto River in central Ohio are strongly influenced by local geologic conditions. These data allow the development of a potential ground-water yield map (from Pettyjohn and Hennings, 1979).

Upper number is low flow, mgd.
Lower number is low flow, mgd/sq mi.

Area of surficial outwash; well yields may exceed 1000 gpm.

Area of outwash covered by a few feet of alluvium; well yields commonly between 500 and 1000 gpm.

Generally fine-grained alluvium along flood plain; well yields usually less than 25 gpm.
Figure 15. Streambeds and banks are unique environments because they are where ground water that drains much of the subsurface of landscapes interacts with surface water that drains much of the surface of landscapes.
Figure 14. Surface-water exchange with ground water in the hyporheic zone is associated with abrupt changes in streambed slope (A) and with stream meanders (B).
Most wetlands are GW discharge areas
Winter 1988

Area favorable for wetland formation

Direction of groundwater flow

Break in slope

Water table

Line of equal hydraulic head
C

Area favorable for wetland formation

Water table

Direction of groundwater flow

Line of equal hydraulic head

EXPLANATION

\[ K = \text{HYDRAULIC CONDUCTIVITY} \]

Winter, 1988
FENS

- SCANDANAVIAN WORD FOR WINDOW
- GW MOVING VERTICALLY UPWARD FROM A CONFINED AQUIFER THRU A CONFINING UNIT
- FLOW RATE AND CHEMISTRY ARE CONSTANT
- RESULTS IN A UNIQUE, HIGH QUALITY WETLAND
  - SPECIES DIVERSITY
CWA 404 Issues – Preferential GW flow to a 70 acre alpine wetland – Summit Cy, CO from Kolm & Allen, 2001
Calcareous fens typically occur as seeps and springs associated with discharge from calcareous, confined aquifers. Only groundwater flow in the confined aquifer is shown. Graphic is not to scale.
Figure 6.17 Mechanisms of delivery of rainfall to a stream channel from a hillslope in a small tributary watershed (after Freeze, 1974).
SPRINGS

A) DEPRESSION SPRING

B) CONTACT SPRING

C) FAULT SPRING

D) SINKHOLE SPRING

E) JOINT SPRINGS

F) FRACTURE SPRING

FIGURE 7.12 Types of springs.

FETTER, 1988
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Natural Ground-Water Quality

- Nearly all GW originates as rain or snow that infiltrates to the saturated zone
- Infiltration through soil zone / vadose zone has great influence on chemistry of water
- Soil generates carbonic acid (H2CO3) and consumes dissolved oxygen
Chemistry of GW is controlled by rock-water interaction that occur as gw flows from areas of recharge to areas of discharge

- Increases in total dissolved solids and major ions
- Changes in dominant anions - $\text{HCO}_3 > \text{SO}_4 > \text{Cl}$
- Cation concentrations vary due to reactions
Natural Ground - Water Quality

1. Not well characterized

2. Varies depending on which portion of aquifer (Recharge area vs. discharge area)

3. Assessments typically based only on indicator parameters (TDS, SC)

4. Aquifer monitoring efforts (baseline, ambient) have been greatly reduced in the last decade
Dissolved Constituents in GW

- **Major constituents**
  - (> 5mg/l)
  - Bicarbonate (HCO3)
  - Calcium (Ca)
  - Chloride (Cl)
  - Magnesium (Mg)
  - Silicon (Si)
  - Sodium (Na)
  - Sulfate (SO4)
  - Carbonic Acid (H2CO3)

- **Minor constituents**
  - (> 0.01 -10mg/l)
  - Boron (B)
  - Carbonate (CO3)
  - Fluoride (Fl)
  - Iron (Fe)
  - Nitrate (NO3)
  - Potassium (K)
  - Strontium (Sr)
Dissolved Constituents in GW

Trace constituents (< 0.1 mg/l)

- Aluminum
- Antimony
- Arsenic
- Barium
- Cadmium
- Chromium
- Copper
- Lead
- Manganese
- Lithium
- Phosphate
- Radium
- Selenium
- Silver
- Uranium
- Zinc
Organic constituents

- Important species
  - H2CO3, CO2, HCO3, CO3

- Ubiquitous

- Mostly fulvic & humic acid

Atmospheric gases

- N2, O2, CO2

Gases produced by anaerobic biochemical processes

- CH4, H2S, N2O
pH Range of Natural Waters

predominant species

\[ H^+ \quad H_2CO_3^+ \quad HCO_3^- \quad CO_3^{2-} \quad OH^- \]

\[ SO_4, Cl, F, SiO_2 \quad Cl, SO_4 \quad F \]

Fe, Al, (\pm Cu, Zn) \quad Ca, Mg, Na, K \quad Ca, Mg, SiO_2

-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

most natural waters \rightarrow (most minerals insoluble)

soil waters \rightarrow and bog waters

acid saline lakes \rightarrow

alkaline saline lakes

acid crater lakes

and geothermal waters \rightarrow

hyperacidic

acid mine waters \rightarrow

deep granitic groundwaters (not brines)

hyperalkaline ground waters (ultramafic rocks)
TOTAL DISSOLVED SOLIDS

Classification for GW

- Fresh water – 0-1000 mg/l
- Brackish water – 1000 –10,000 mg/l
- Saline water – 10,000 –100,000 mg/l
- Brine water - > 100,000 mg/l
The Content of Metallic Ions Which React With Sodium Soaps To form Scummy Residue

- Soft - < 60 mg/l
- Hard - 80 - 100 mg/l
- Very Hard - > 150 mg/l

Water softening common when hardness > 80 mg/l

Typically total concentration of Ca$^{2+}$ + Mg$^{2+}$
Expressed as mg/l equivalent CaCO3

GW in mountain watersheds underlain by granitic/metamorphic rocks is typically soft
FIGURE 9.8 Analysis represented by Stiff patterns. The horizontal distance from the vertical axis is based on the number of milliequivalents per liter of each anion or cation. Use of the lower bar for iron and carbonate is optional. Source: J. D. Hem, U.S. Geological Survey Water-Supply Paper 2254, 1985.
Isotopes in GW

- Elements that have same # of protons in nucleus but different # of neutrons
- Same atomic # but different atomic weight
- Slightly different chemical properties
- Stable isotopes vs. radioisotopes
- Useful as tracers
## Isotopes Commonly Used in Hydrogeology

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Symbol</th>
<th>Molecule</th>
<th>Type</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deuterium</td>
<td>D</td>
<td>H\textsubscript{2}O</td>
<td>Stable</td>
<td>---</td>
</tr>
<tr>
<td>Oxygen- 18</td>
<td>\textsuperscript{18}O</td>
<td>H\textsubscript{2}O</td>
<td>Stable</td>
<td>---</td>
</tr>
<tr>
<td>Tritium</td>
<td>\textsuperscript{3}H</td>
<td>H\textsubscript{2}O</td>
<td>Radiogenic</td>
<td>12.7 years</td>
</tr>
<tr>
<td>Sulfur- 35 (1)</td>
<td>\textsuperscript{35}S</td>
<td>SO\textsubscript{4}\textsuperscript{2-}</td>
<td>Radiogenic</td>
<td>87 days</td>
</tr>
<tr>
<td>Carbon – 14</td>
<td>\textsuperscript{14}C</td>
<td>CO\textsubscript{2}</td>
<td>Radiogenic</td>
<td>5730 yrs</td>
</tr>
</tbody>
</table>

(1) – Still in proof of concept
Isotopic Ratios for Oxygen

Isotopic concentrations are expressed as the difference the measured ratios of the sample and reference divided by the measured ratio of the reference. This is expressed using the delta (d) notation:

\[
\delta^{18}\text{O}_{\text{sample}} = \frac{m(\text{^{18}O/^{16}O})_{\text{sample}} - m(\text{^{18}O/^{16}O})_{\text{reference}}}{m(\text{^{18}O/^{16}O})_{\text{reference}}}
\]

✓\(^{18}\text{O} / \text{^{16}O}\) Ratio is changed by fractionation processes

✓Snow –depleted in \(^{18}\text{O}\); rain enriched in \(^{18}\text{O}\)
Tritium (\(^3\)H) In The Environment

- Produced by cosmic rays spallation of nitrogen
  - Pre-bomb < 10TU in precip

- Nuclear weapons testing - 1953 - 1962
  - Up to 1000 TU in precip in 1964
  - 2000 - Tritium in precip approaching pre-bomb levels

- GW mean residence times based on tritium
  - < 0.8 TU - recharged prior to 1952
  - 5 - 15 TU - modern - (<5 to 10Yrs)
  - > 30 TU - Considerable % of recharge from 1960’s / 70’s
  - > 50 TU - Dominantly 1960’2 recharge
Uses for isotopic data

- Determine gw recharge areas
- Evaluate gw flowpaths
- Determine sources of TDS
- Relative age of gw – (length of time that gw has been out of contact with atmosphere)
Water Quality Standards

- Standards established in USA and Western Europe for:
  - Inorganic contaminants
  - Pesticides/PCBs/Herbicides
  - Volatile Organic Chemicals
  - Other organic chemicals
  - Radio-nuclides
  - Microbiological Contaminants
Global GW Issues

- **Central Valley CA** (Colin, A, 2014)
  - 160 km$^3$ of GW withdrawal in last 150 yrs (176 billion tons)
  - More than 25 feet of subsidence – increased rate in 2014-15
  - Resulted in annual uplift of 3mm /yr in California Coastal Ranges / southern Sierra Nevadas
  - Also results in differential hydraulic pressures on fault planes – mini-earthquakes

- **Global withdrawals** (Konikow, 2011)
  - 1900-2008 - 4500 km$^3$ GW withdrawal
  - = 12.6 mm sea level rise (> 6% of total)
  - 2000 -2008 – ave. 145 km$^3$

- **Off shore fresh GW** (Post, et al, 2013)
  - Large volumes of low-salinity GW beneath continental shelves – due to recharge by meteoric water during low sea-level times
THANK YOU!
Mike Wireman

Ama Dablam
Khumbu, Nepal
Hydrogeologic setting

ALLUVIAL MOUNTAIN VALLEY

> THIN, BOULDERY ALLUVIUM OVERLYING FRACTURED BEDROCK

> ALLUVIUM DERIVED FROM SURROUNDING SLOPES - WATER OBTAINED FROM SAND & GRAVEL INTERSPERSED BETWEEN FINER GRAINED DEPOSITS

> DEPTH TO WATER IN ALLUVIUM TYPICALLY SHALLOW BUT QUITE VARIABLE - HYDRAULICALLY CONNECTED TO UNDERLYING FRACTURED BEDROCK