Yangxiao Zhou PhD
Associate Professor of Hydrogeology

https://www.researchgate.net/profile/Yangxiao_Zhou/citations?sorting=recent

- Coordinator of WSE HWR03 Hydrogeology and lecturing Steady groundwater flow
- WSE HWR 07b Groundwater data collection and interpretation; lecturing Groundwater monitoring and hydrogeostatistics
- Coordinator of WSE HWR10 Applied groundwater modelling and lecturing groundwater flow and contaminant transport modelling

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- Supervision of MSc students
  - Groundwater modelling
  - Groundwater-surface water interactions
- Supervision of PhD students
  - Groundwater-surface water interactions
  - Modelling of managed aquifer recharge systems
- Capacity development project
  - Saltwater intrusion in coastal areas
  - Managed aquifer recharge

Participants 2018-2020

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1053168	Eunice Shisiali Ashiono
1054345	Nithin Achutha Shettigar
1056683	Prince Clive Ogutu
1057242	Kumar Baral
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1058350	Sammy Juma Nyongesa
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Module WSE HWR03 Hydrogeology

Objectives

- Describe groundwater occurrence, aquifer classification and aquifer properties;
- Comprehend the concepts related to groundwater storage, recharge and discharge and compute water balance;
- Describe Darcy's equation and apply it to formulate partial differential equations for groundwater flow and water balance computation;
- Analyse steady natural groundwater flow in aquifers;
- Analyse steady groundwater flow to wells in aquifers and compute aquifer parameters from pumping test data;
- Apply principles of superposition and image to solve more complex problems of flow to wells

Module WSE HWR03 Hydrogeology

Objectives

- Distinguish between phreatic and confined aquifer storages and aquifer parameters to measure these storages;
- Analyse transient natural groundwater flow in unconfined and confined aquifers;
- Analyse transient groundwater flow to wells in aquifers and compute aquifer parameters from pumping test data;
- Formulate plans for groundwater development and management.

Hydrogeologists

- Hydrogeoloical investigations
- Groundwater resources assessment
- Water supply
- Groundwater monitoring
- Protection of groundwater resources
- Remediation of groundwater pollution
- Impacts of groundwater development on environment
- Groundwater resources management

Module Hydrogeology

- Pre-requisites
  - Geology;
  - Hydrology;
  - Calculus;
  - Partial differential equations;
  - Basic hydraulics.

Module Hydrogeology

- Hydrogeology, 10 periods, Tibor Stigter
- Groundwater hydraulics, 20 periods
  - Yangxiao Zhou, Steady flow, 10 periods
  - Theo Olsthoorn, Transient flow,10 periods
- Examination
  - Written exam: 70%
  - Assignments: 30%

Module Hydrogeology

- Lecture materials
  - **https://ecampusxl.unesco-ihe.org/course/view.php?id=951**

    2017/2019-WSE/HWR/03/s: Hydrogeology
  - **Public folder: IHE menu/Public folders staff/zyxpublic/Steady Groundwater Flow**

Groundwater Hydraulics

- Lecture plan
  - Period 1: Introduction; Basic Equations
  - Period 2: Basic equations; Flow in confined aquifer;
  - Period 3: Flow in unconfined aquifers;
  - Period 4: Flow in semi-confined aquifers;
  - Period 5: Radial flow in confined aquifers;
  - Period 6: Radial flow in unconfined aquifers;
  - Period 7: Radial flow in semi-confined aquifer;
  - Period 8: Method of superposition;
  - Period 9: Method of images; Flow net;
  - Period 10: Q&A.

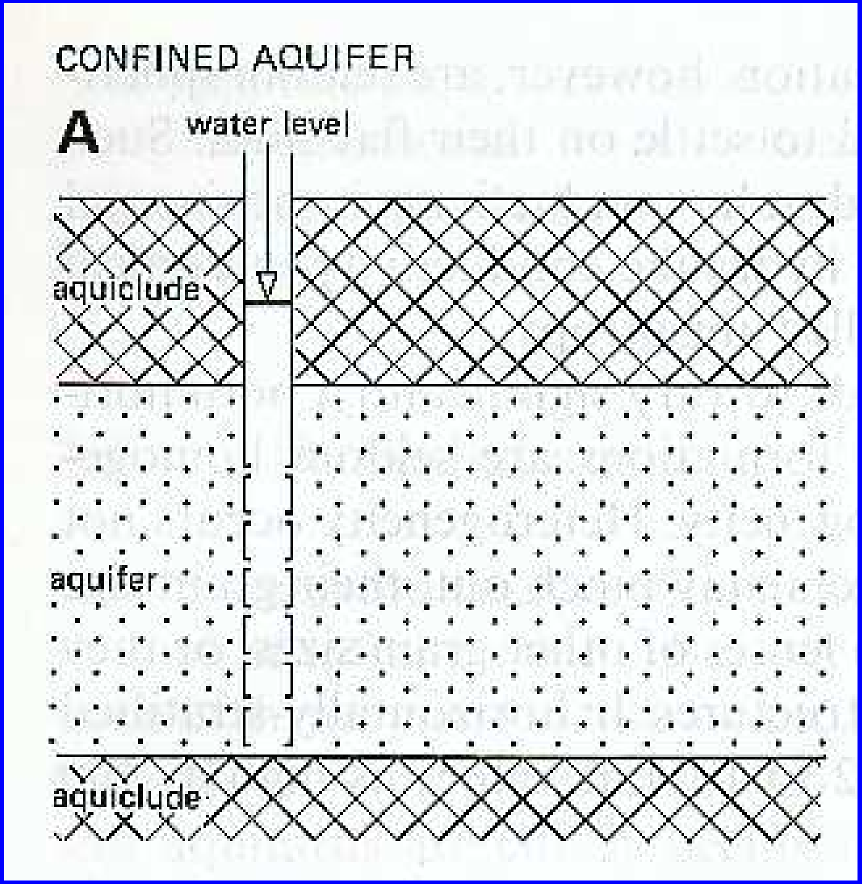
Groundwater hydraulics

- Aquifers (confined, unconfined, semi-confined)
- Boundaries (constant, variable)
- Sources/sinks (constant, variable)
- Hydraulic head (groundwater level above msl)
- Darcy's law
- Mass conservation (balance)
- Equations of groundwater flow
- Solutions of natural groundwater flow
- Solutions of groundwater flow to a pumping well
- Analysis of pumping test data

Aquifers

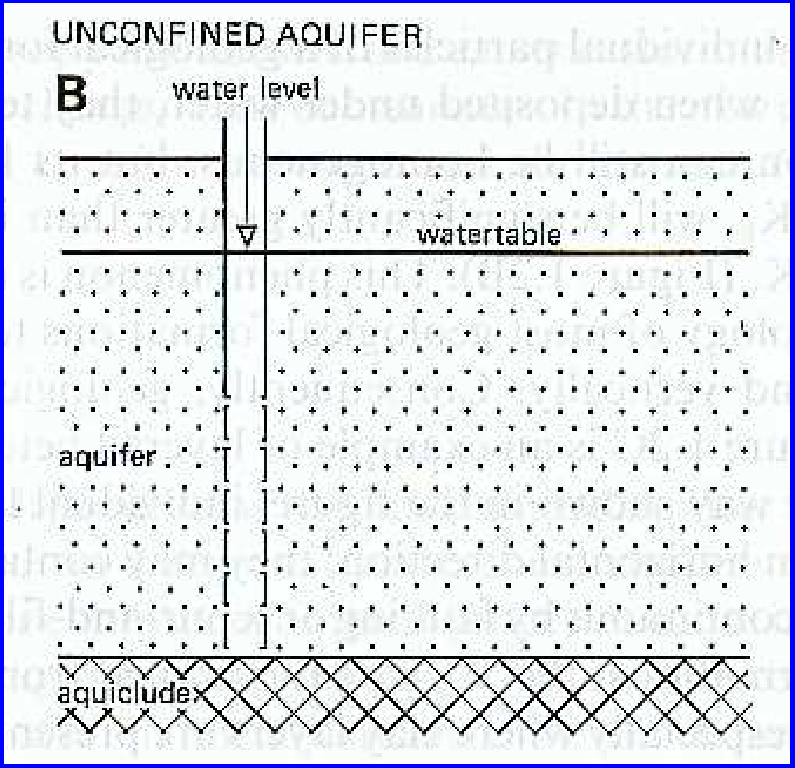
- Aquifer: saturated permeable geological formations with large water storage and high transmissivity: gravel, sand, sandstone, limestone, ….
- Aquitard: geological formations with good water storage but small transmissivity: silt, sandy clay, shale, ….
- Aquiclude: impermeable geological formations with poor water storage and poor transmissivity: thick clay layer, dense unfractured mudstone, igneous and metamorphic rocks, ….

Confined aquifers



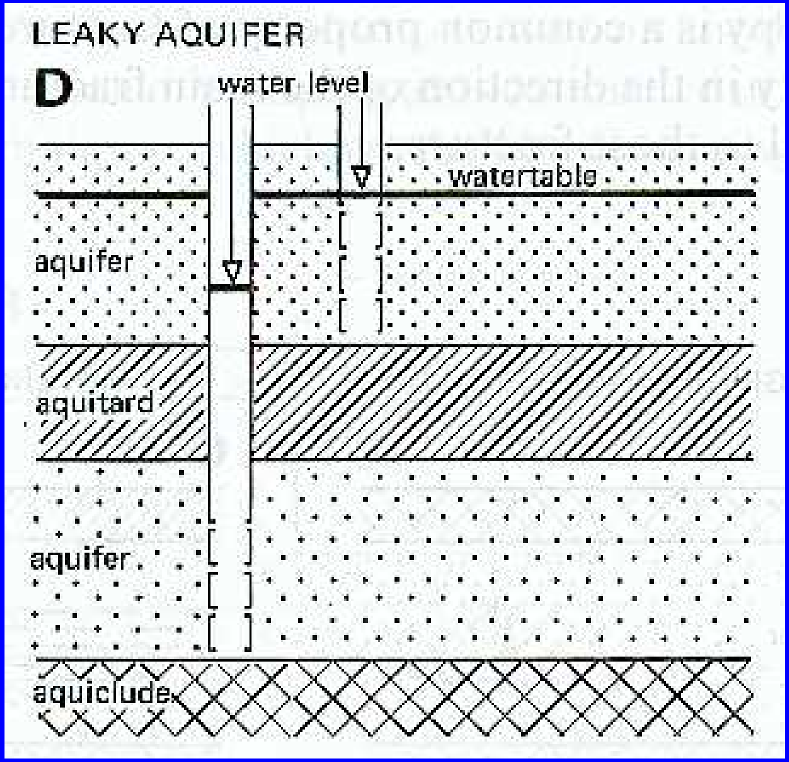
- A confined aquifer is bounded above and below by an quiclude. Groundwater level is usually higher than the top of the aquifer, or even above the ground surface. The aquifer then is called artesian aquifer.

Unconfined (Phreatic) aquifers



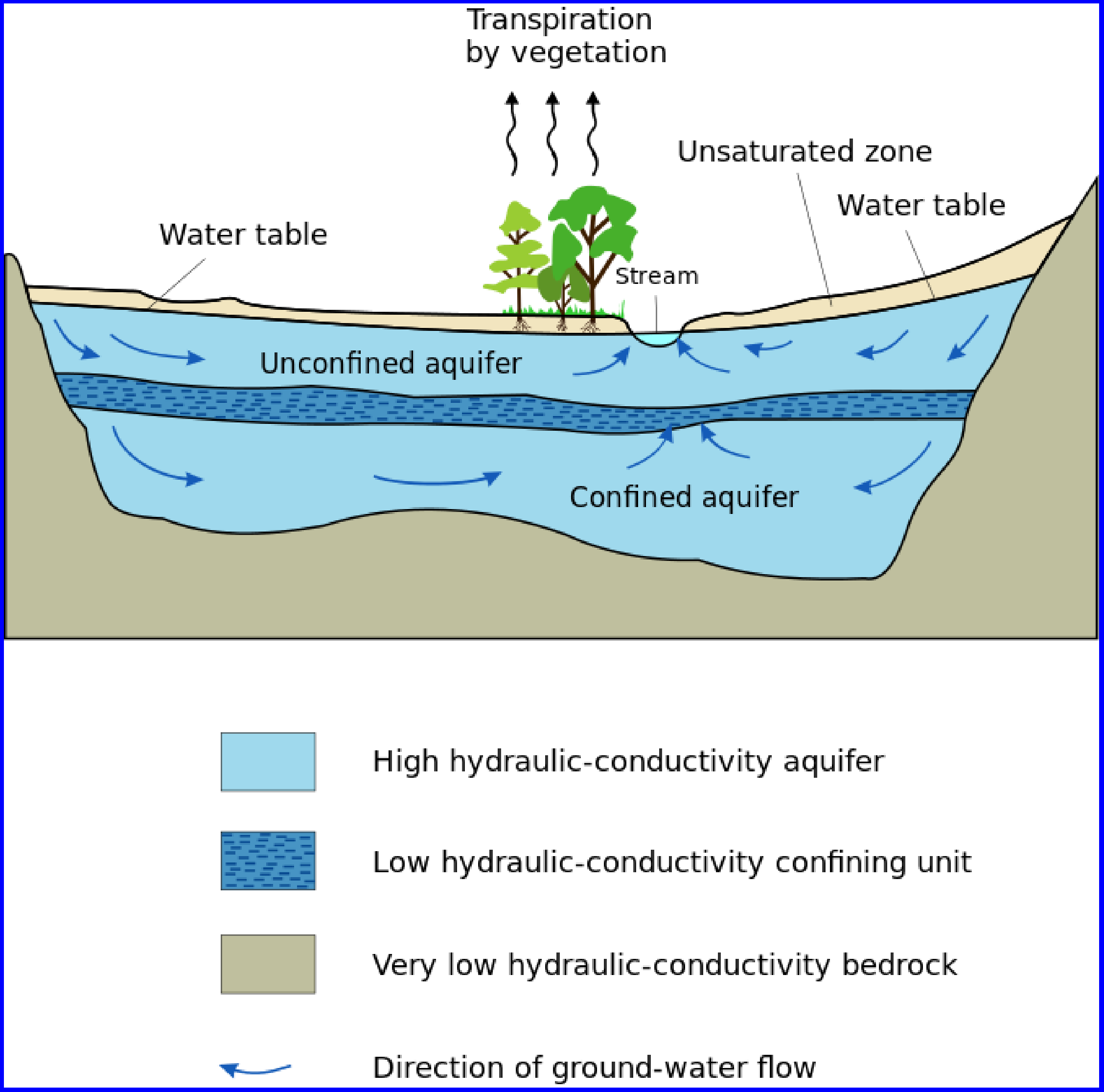
- An unconfined aquifer is bounded below by an aquiclude, but is not restricted by any confining layer above it. Its upper boundary is the water table, which is free to rise and fall.

Semi-confined (Leaky) aquifers



- A semi-confined aquifer is bounded above and/or below by aquitards. Water is free to flow through the aquitards, either upward or downward depending on head difference.

Semi-confined (Leaky) aquifers



Properties of aquifers

- Porosity, n
- Effective porosity, n_e
- Specific yield, μ (S_y)
- Specific storage, S_s
- Storage coefficient, S
- Hydraulic conductivity, K
- Intrinsic hydraulic conductivity, κ
- Transmissivity, T
- Vertical leakance or resistance, V_k or c

Boundaries

- Specified head boundaries
  - Large rivers and lakes
  - Sea/Ocean
  - Distant boundary
- Specified flow boundaries
  - Rivers and lakes
  - Underflow
  - Local hydraulic boundary
- No-flow boundaries
  - Impermeable rock and fault zone
  - Groundwater divide
  - Freshwater/saltwater interface

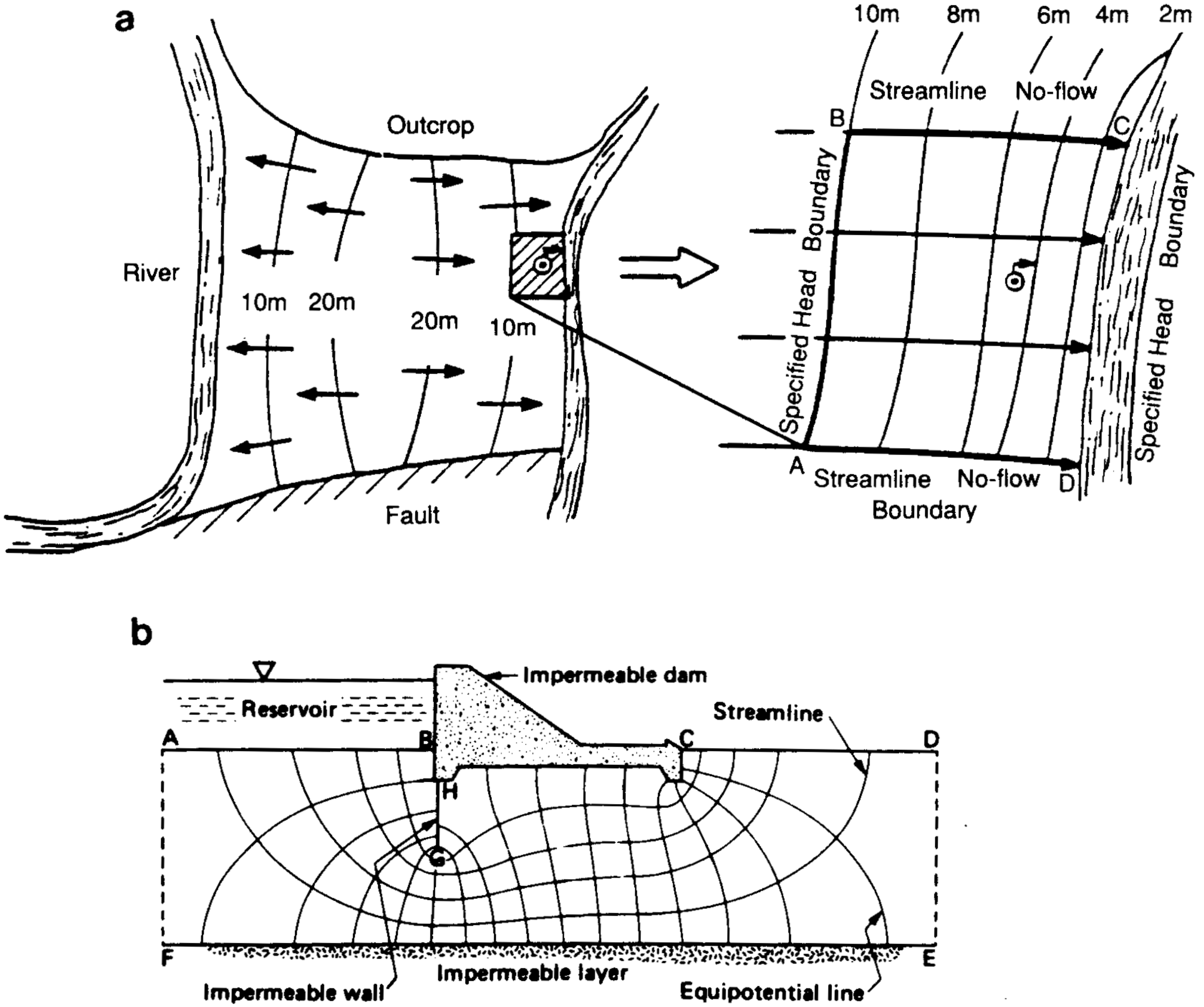


Fig. 4.7 Hydraulic boundaries.
(a) Water table contour maps showing a regional problem domain on the left with physical boundaries and a local problem domain on the right with three hydraulic boundaries (Townley and Wilson, 1980).
(b) AF and DE are no-flow streamlines used as hydraulic boundaries for a problem involving flow through a dam (Franke et al., 1987).

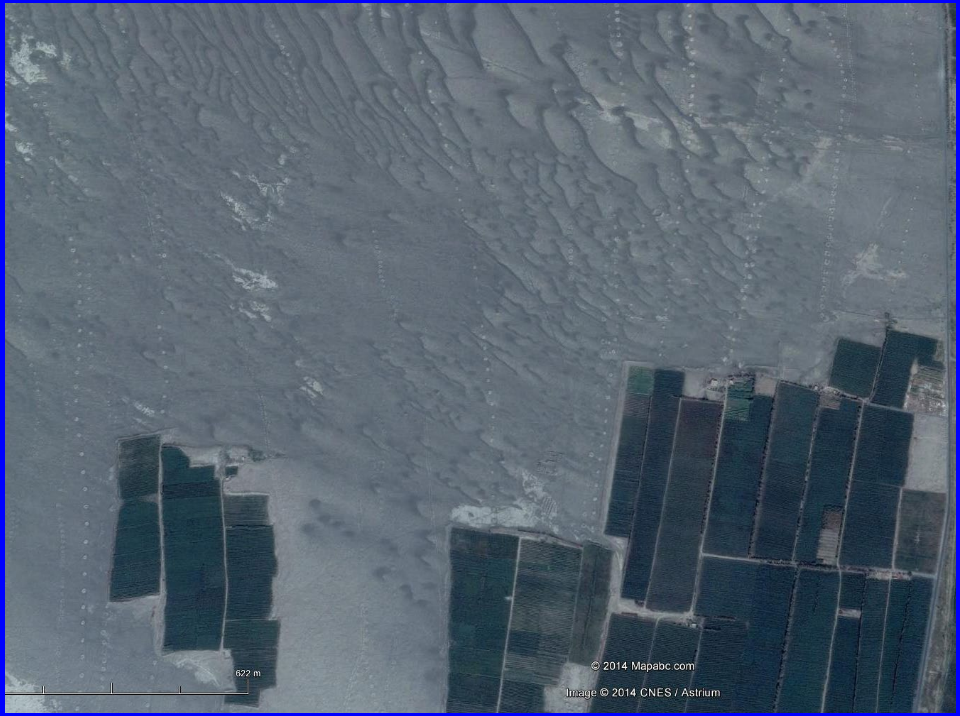
Sources/sinks

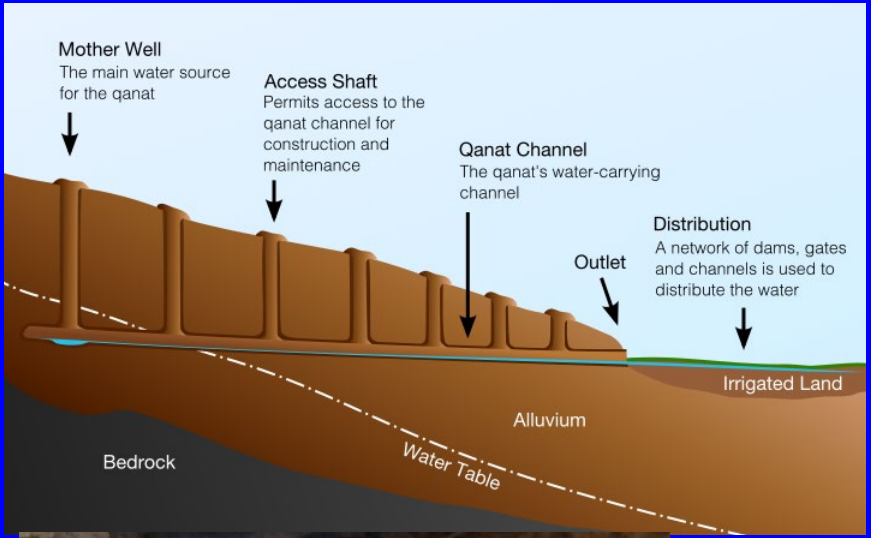
- Sources
  - Recharge from precipitation infiltration
  - Leakage from surface water bodies
  - Artificial recharge
- Sinks
  - Abstraction with pumping wells
  - Spring discharges
  - Discharge to surface water
  - Evapotranspiration

A brief review of historical development

- Ancient civilizations directly used spring water as drinking water.
- Qanat system to divert groundwater for water supply and irrigation was invented as early as 1000 years B.C. in Iran.
- Dug wells with large diameters were constructed in China more than 2000 years ago. The walls of the wells were reinforced by bamboo, potteries and later by bricks.
- Tube wells were drilled since 12th century in Europe to tap groundwater in even larger depth.

Qanat system in Turfan Basin China





A brief review of historical development

- The design of a pumping well required knowledge of pumping rate in relation to drawdown and aquifer properties.
- Henry Darcy was in charge of a public water supply project for the City of Dijon between 1832-1840. He constructed water supply system consisting of 2 reservoirs, a 12.7km aqueduct to transfer the water to Dijon, and 120 street fountains for domestic use. The report entitled "The Public Fountains of the City of Dijon" was published only in 1856. In the Appendix D, Darcy described his famous laboratory experiment of water flow through sand column and the resulted empirical law of discharge linearly proportional to hydraulic gradient. This is the well-known Darcy's law, the foundation of scientific hydrogeology.

A brief review of historical development

- Another French hydraulic engineer, Jules-Juvenal Dupuit derived steady radial flow to a well in an unconfined aquifer and in a confined aquifer in 1863. The assumption of horizontal flow in the case of a gravity well in an unconfined aquifer, is used even today and is referred to as the Dupuit assumption.
- The same and similar solutions were found by a Austria scientist Phillipp Forchheimer (1886), a America scientist Slichter (1899), and a German groundwater scientist Gunther Thiem (1906).
- Transient radial flow to a well in a confined aquifer was found by Theis in 1935. It was Jacob (1940) formally derived the partial differential equation, solution and defined the physical meaning of storage coefficient.

A brief review of historical development

- Steady radial flow in a semi-confined (leaky) aquifer was first approached by Kooper in 1914 and solved comprehensively by De Glee in 1930 in The Netherlands.
- The same solution was published much latter by Jacob in 1946. Since then, the solution was extended to transient radial flow in a leaky aquifer (Hantush and Jacob 1955), to elastic storage release from the aquitard (Hantush 1960; Neuman and Witherspoon 1969).
- The solutions of multiple layered aquifer systems were published in late 20^{th} (Hemker 1984 and 1985; Hunt 1985; Maas 1986 and 1987a,b; Hemker and Maas 1987; Wu 1987; Cheng and Morohunfola 1993).

A brief review of historical development

- Many text books were dedicated to groundwater hydraulics, some examples are:
  - Groundwater and Seepage by Harr (1962);
  - Theory of Groundwater Flow by Verruijt (1970);
  - Dynamics of Fluids in Porous Medium by Bear (1972);
  - Hydraulics of Groundwater by Bear (1979);
  - Groundwater Hydraulics by Halec and Svec (1979);
  - Analytical Solutions of Geohydrological Problems by Bruggeman (1999);
  - Groundwater Hydraulics by Sato and Iwasa (2003);
  - Groundwater Hydraulics and Pollutant Transport by Charbeneau (2006).
- They all focus on pumping rate – drawdown relations and use of these relations for analysis of pumping test data.

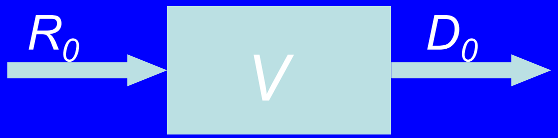
New development

- Water balance and sources of water to the well
- Travel time and mean residence time
- Well protection zones

New development

- Water balance and sources of water to the well
  - Natural condition: natural recharge equals natural discharge

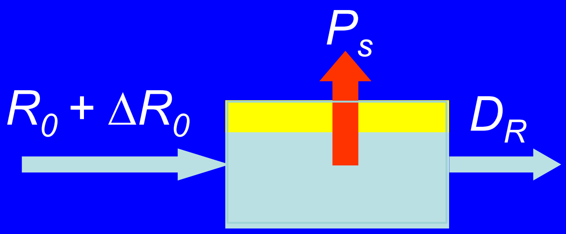
$$R_0 = D_0$$



– Pumping condition

$$(R_0 + \Delta R_0) - (D_0 - \Delta D_0) - P = \frac{dV}{dt}$$

$$P_s = R_0 + \Delta R_0 - D_R$$



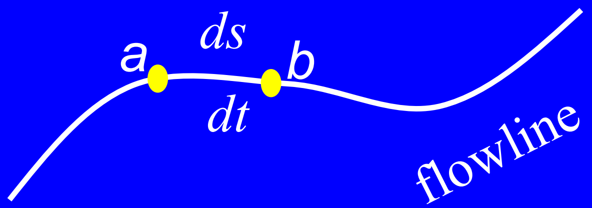
ΔR_0: increased recharge; ΔD_0: decreased discharge (positive);
dV/dt: change of groundwater storage, P_s is the sustainable pumping rate and D_R is the residual discharge.

New development

- Travel time and mean residence time

–Groundwater flow velocity

$$v = \frac{ds}{dt}$$

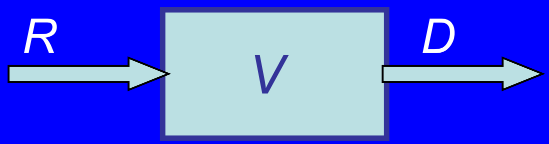


–Groundwater travel time along a flowline

$$t = \int_a^b \frac{ds}{v}$$

–Mean residence time: average amount of times all water particles reside in the aquifer: aquifer renewable time or depletion time:

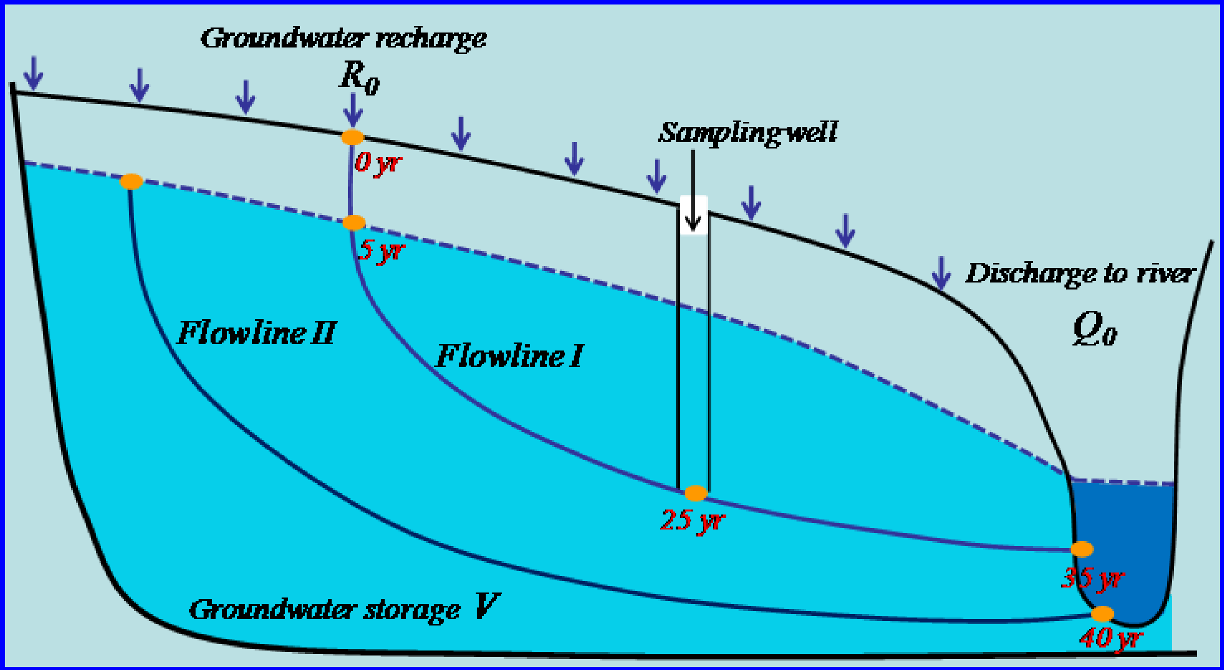
$$\tau = \frac{V}{Q}$$



V is the storage (m^3), and Q is the flow rate (m^3/day)

New development

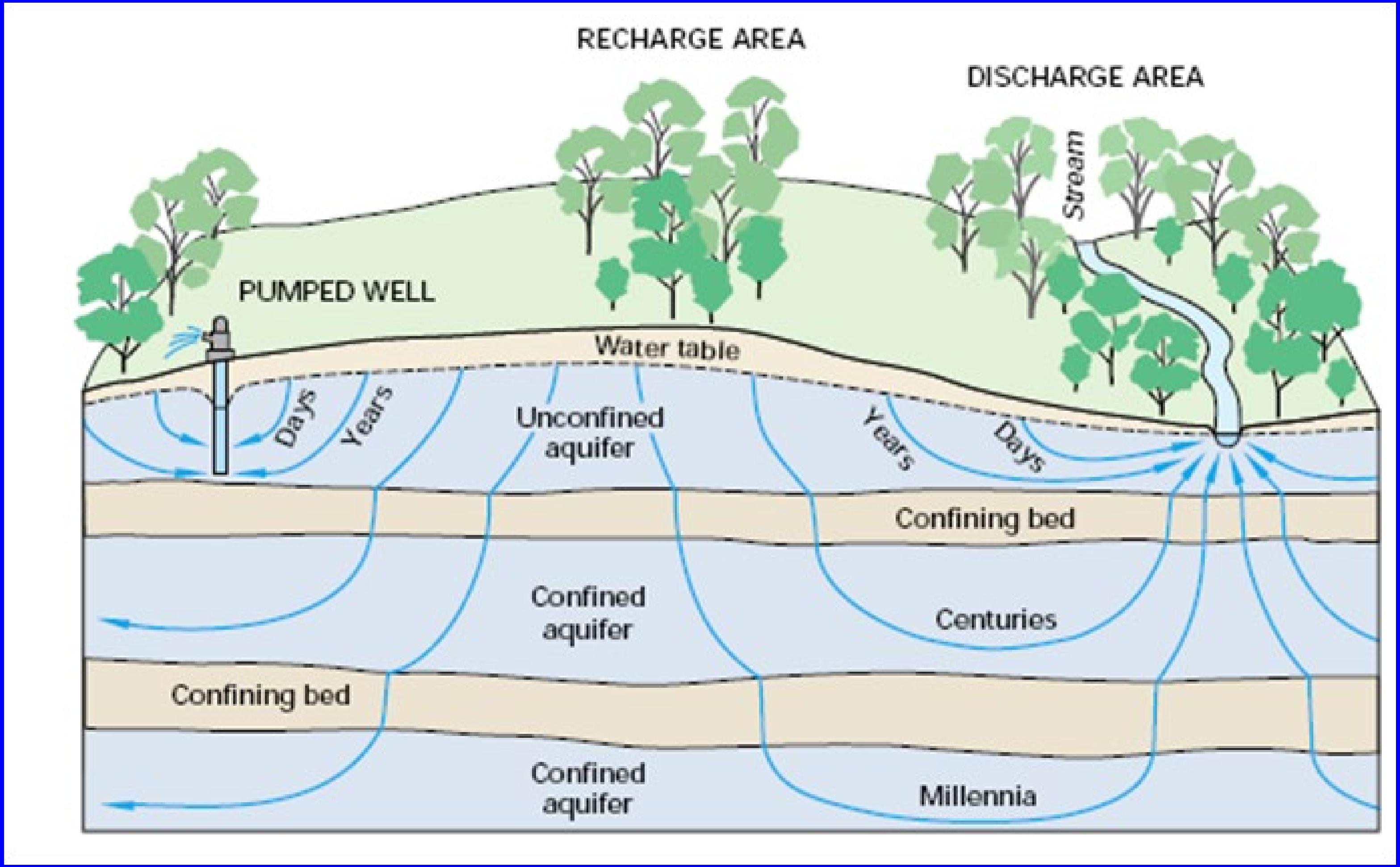
- Determination of residence time
  - Solution of travel time equation by analytical method
  - Particle tracking method combined with a numerical model
  - Groundwater age dating with radioactive isotopes



Flowline I: travel time of a recharged water through the unsaturated zone is 5 years; from water table to the sampling well is 20 years; and from sampling well to the river is 10 years. Groundwater age is 25 years old at sampling well, and 35 years old at the river. The residence time from water table to the river is 30 years.

New development

- Determination of residence time



Residence times of groundwater from water table to a discharge stream or a well in various flow systems (from Winter et al., 1998)

New development

- Well field protection zones include:
  - A wellhead protection zone around the well;
  - A inner protection zone for the reduction of pathogens;
  - A outer protection zone for dilution and effective attenuation of slowly degrading substances to an acceptable level;
  - The remaining capture area of the well filed.

New development

- Criteria for delineating protection zones:
  - Distance criterion defines the protection area around a pumping well with a radius;
  - Drawdown criterion defines the protection area as the zone of influence (cone of depression of a pumping well);
  - Travel time criterion bases the boundary of the protection area on the time required for contaminants to reach the pumping well;
  - Flow boundary criterion includes groundwater divide and inflow boundaries;
  - The assimilative capacity criterion is based on the geological formation's capacity to dilute or attenuate contaminant concentrations to the acceptable level before they reach the pumping well.

New development

- Methods for delineating protection zones:
  - Arbitrary fixed radius.
  - Calculated fixed radius.
  - Simplified variable shapes.
  - Analytical methods.
  - Hydrogeological mapping.
  - Numerical models of groundwater flow and/or contaminant transports to delineate the capture zone of the wells or well fields and plot isochrone map and/or contaminant concentration map to define the protection area.

New development

- Well field protection zones in The Netherlands

Protection zones	**Wellhead protection**	**Inner protection zone**	**Outer protection zone**	**Remaining capture area**
Travel time		60 days	10 years to 25 years	
Radial distance	30 m	Around 10 to 150 m	Around 800 to1200m, respectively	
Protection against		Pathogenic bacteria and viruses; Chemical pollution sources	Hardly-degradable chemicals	
Limits of activities	Owned by the water supply company. No any activity is allowed.	Only activities in relation to water supply are admissible	Following activities are not admissible: - transport and storage of dangerous goods - industries - waste-sites - building - military activities - intensive agriculture and cattle breeding - ground-, sand- or limestone pits - waste water	Application of act on soil and groundwater protection

Drinking Water Monitoring in The Netherlands

- Monitoring by water supply companies
  - Legal obligation: every 3 months for major components and every month for bacteria from extracted water
  - Safeguarding of the provision of drinking water: location of monitoring wells with travel time smaller than 25 years
  - Early warning: which parameters hold risks for the drinking water quality
  - To reassure customers on the drinking water quality