11.479J / 1.851J Water and Sanitation Infrastructure in Developing Countries
Spring 2007

A Brief Global and Western History of Water Supply and Sanitation

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Water/Sanitation - Week 10

11.479 J / 1.851 J

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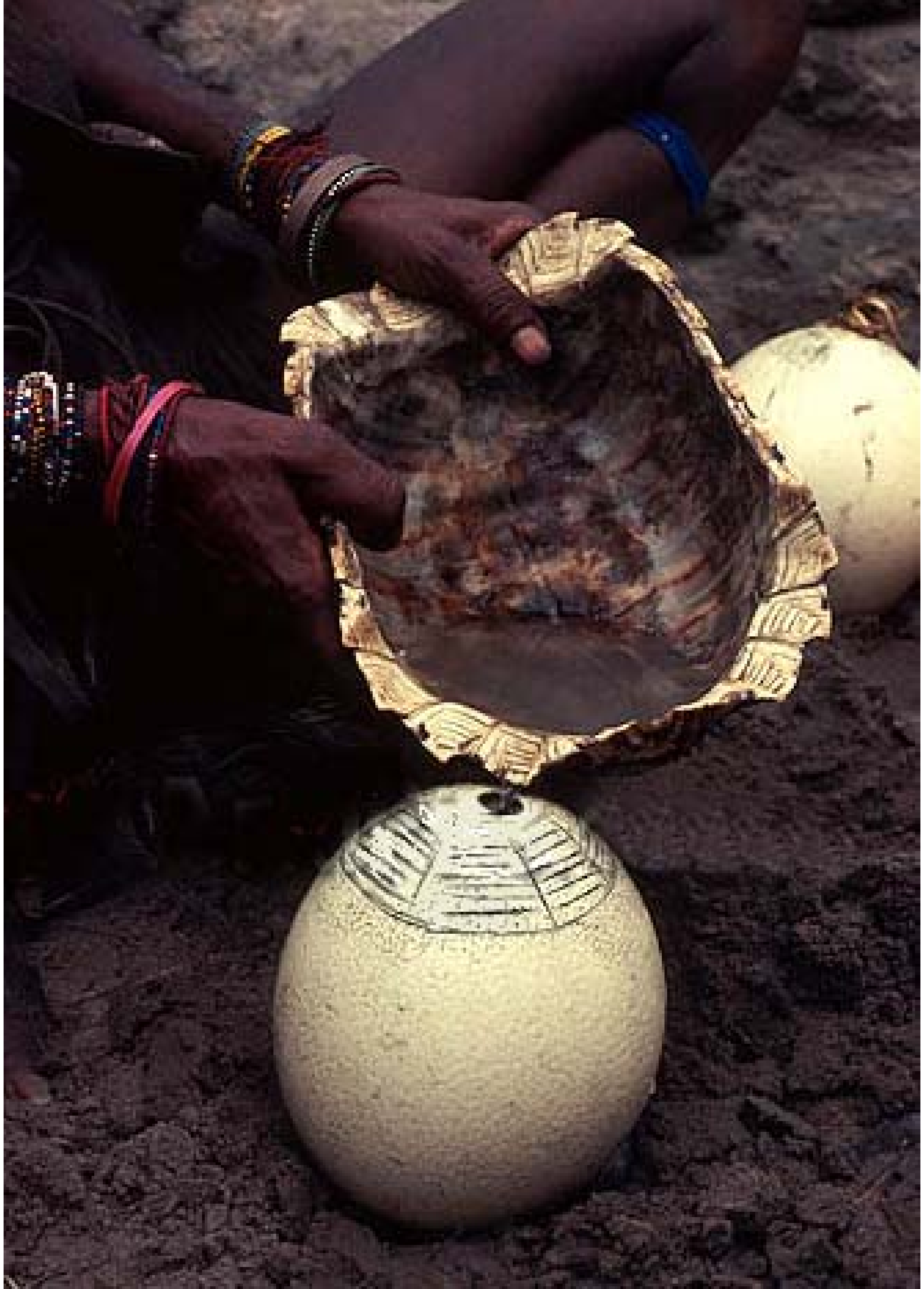
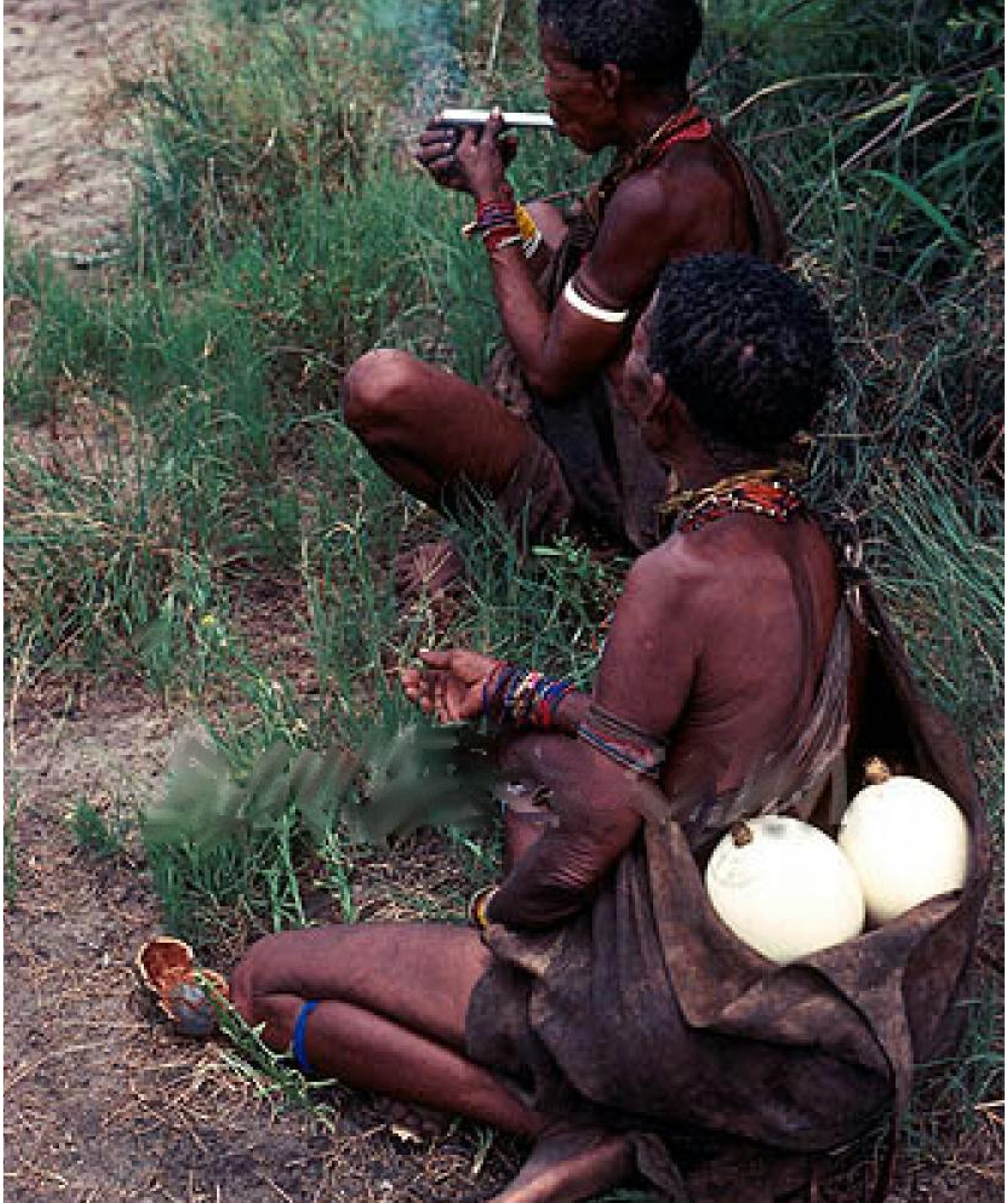
Acknowledgements: Sections of this lecture are adapted from a lecture & book by Alice Outwater, Water – A Natural History, with permission, and research assistance from Ralph Coffman

Prehistoric and present day hunter-gather cultures, such as the Bushman of southern Africa, live in close proximity to their water sources and access water via simple collection and storage vessels



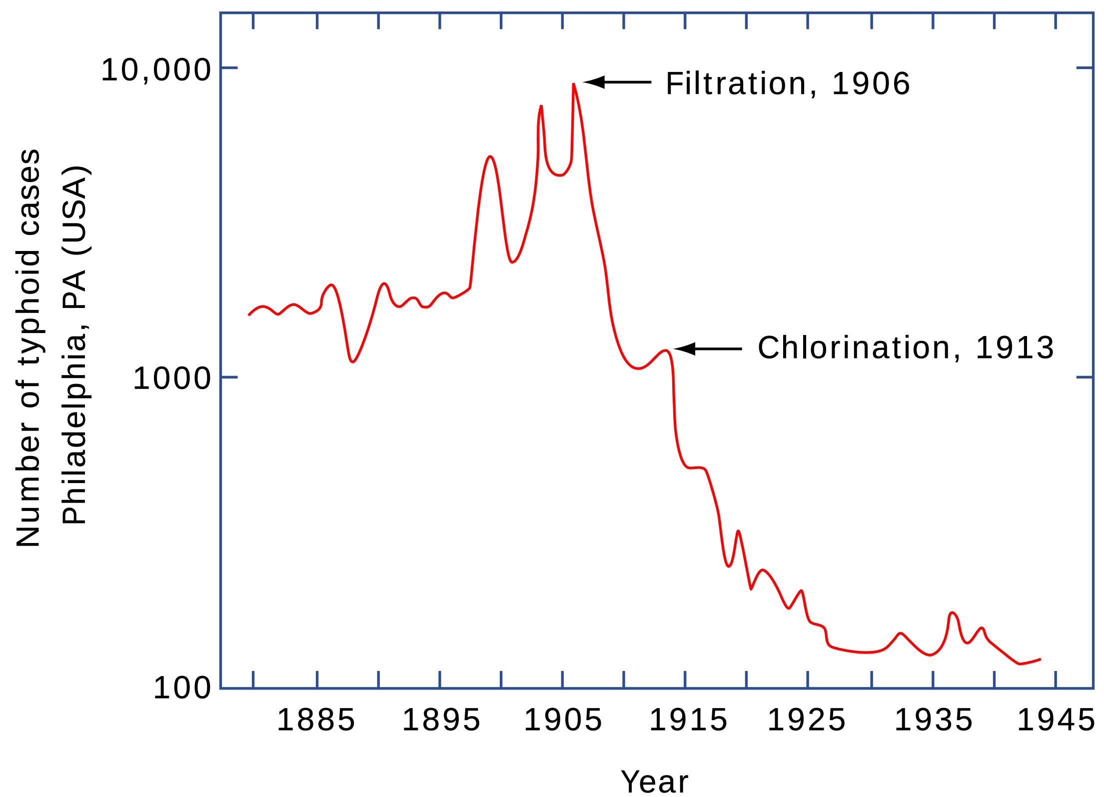


Ostrich Eggs

- Ostrich eggs were used for water collection and storage technology in desert areas
- Adapted by the Bushmen culture of southern Africa
- Used for the last 10,000 years, at least

The “Sanitary Revolution”

- For most of human history, life expectancy at birth for hunter-gatherers was about 25 years
- In Europe of the 1820s, it was still only 40 years.
- Beginning in the 19th century, this picture began to change dramatically.
- One of the most powerful forces for change in life expectancy, child survival and public health was the “sanitary revolution” of the 19th century.



This graph shows the dramatic reduction in typhoid fever cases in response to water purification advances.

Figure by MIT OpenCourseWare.

Paleolithic Water Management

- Time Period
  - Last Glacial Maximum up to 12,000 BP
- Water Sources
  - Edges of glaciers where animals congregate
  - Glacial streams and rivers
  - Paleo-lakes formed from melting glaciers
- Settlements are small and dispersed
- Water Supply
  - directly accessed

Paleo-Lake Cochise (Estacia) NM

Mesolithic Water Management

- Period of northward retreating glaciers
- Time Period:
  - Varies, but essentially 12,000 BP to ~7,000 BP
- Settlements
  - Larger, some specialization,
  - Incipient domestication of flora and fauna
- Water Supply
  - Directly accessed

Neolithic Water Management

- Time Horizon varies but essentially from ~7,000 BP to 2,000 BP
- Beginning of permanent settlements and agriculture
- Villages begin to develop ,such as Catal Huyuk 6,500-5,500 BCE in south-central Konya Plain, Turkey (Anatolia)
- Ceramic technology allows for vessels to transport water and store it.
- Catal Huyuk water supply – paleo lake nearby on Konya Plain

Riverine Water Management

- Begins in Early Neolithic Period
- Associated with development of larger settlements, social stratification and management of riverine cycles based on astronomical measurements
  - Catal Huyuk, 6,500 BCE
  - Egypt, 3,100 BCE
  - Upper Mesopotamia, 5,500-2,500 BCE
- Continues with later Neolithic cultures
  - Lower Mesopotamia, Sumer 2,500-1,800 BCE
  - Indus River 2,000-1,200 BCE

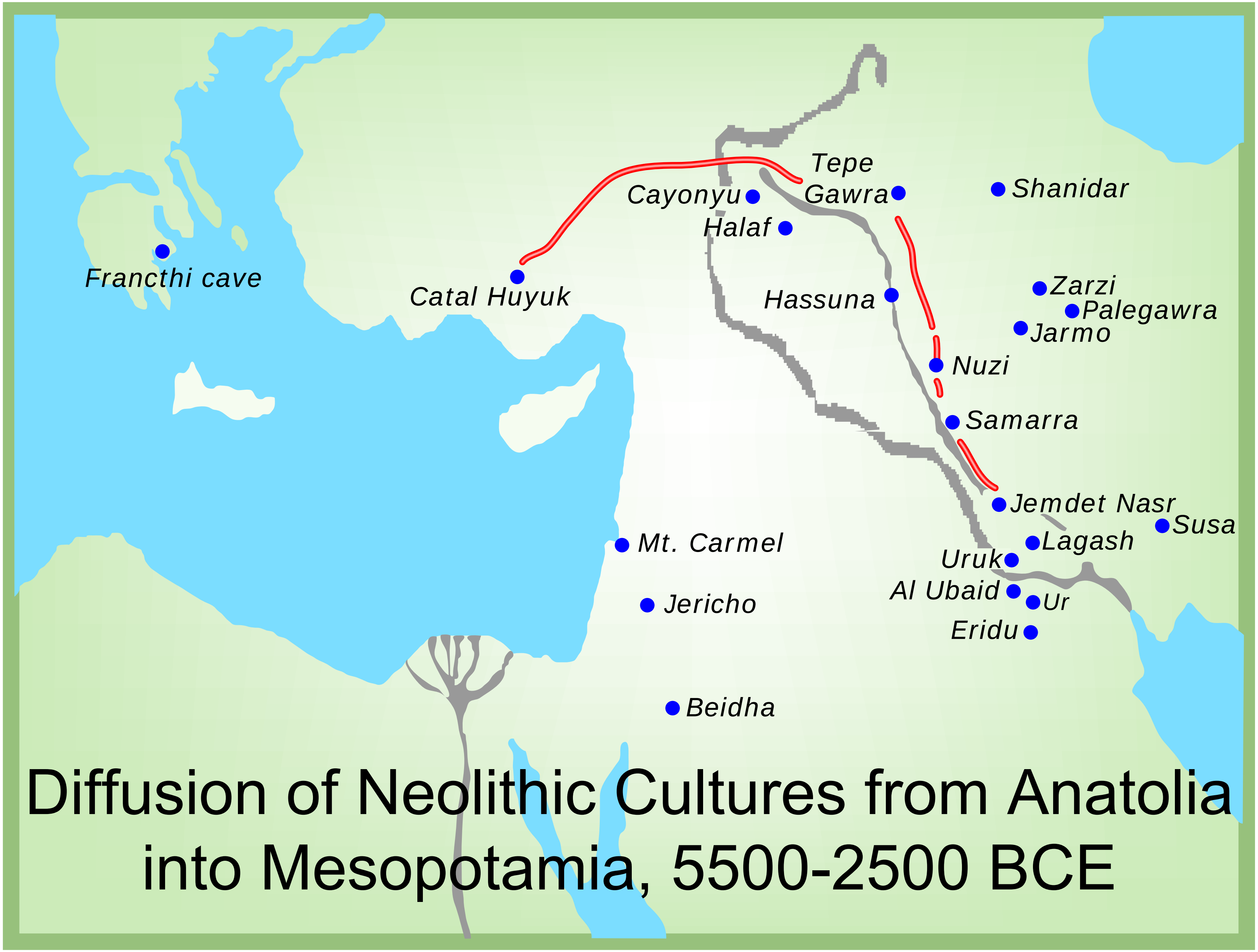


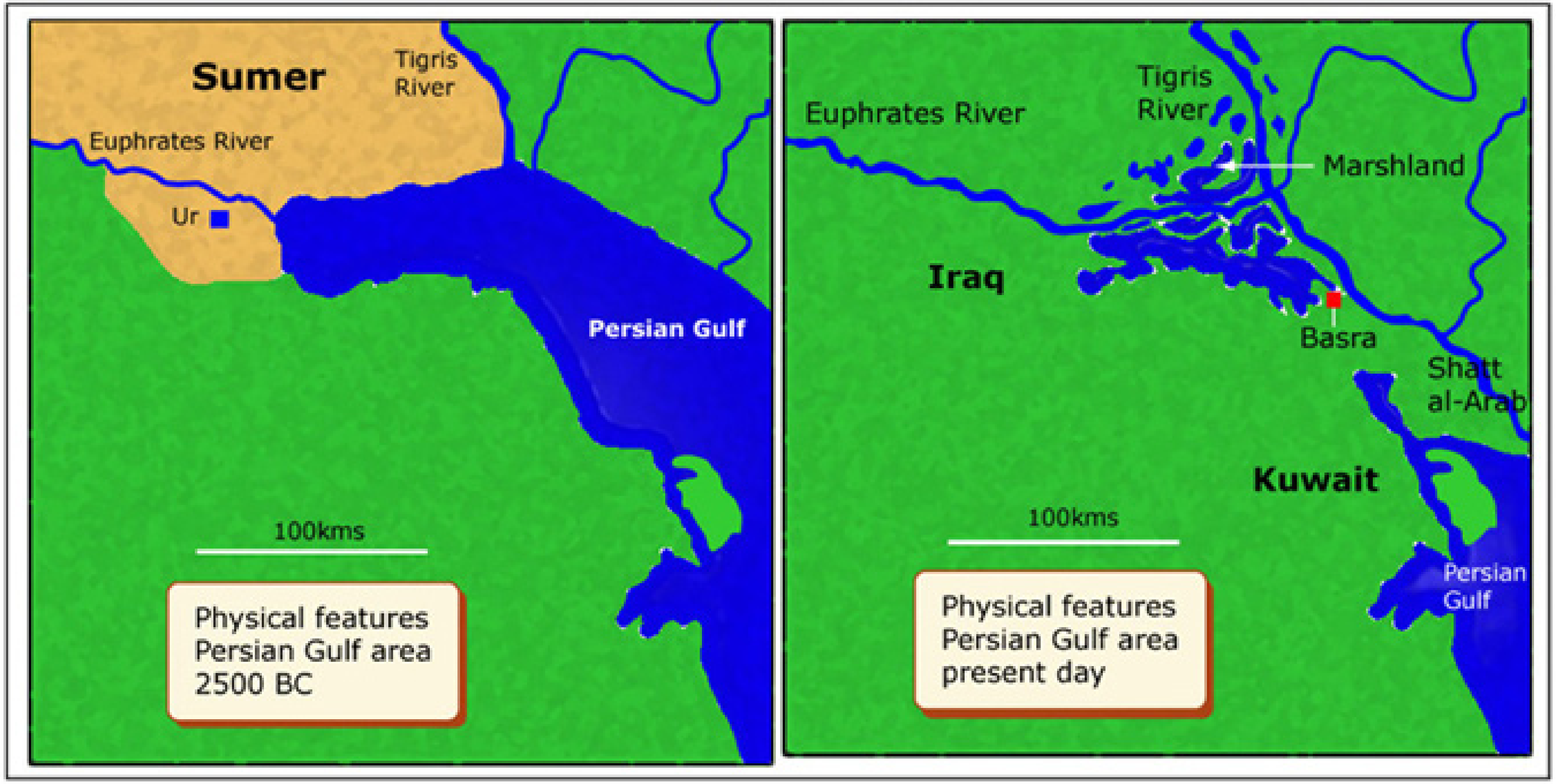
Figure by MIT OpenCourseWare.

Sumeria 2,500 BCE, (Chacolithic Period) Aqueducts in Sumer brought fresh water from remote areas into cities.

Figures by MIT OpenCourseWare.

Persian Gulf

2,500 BCE **2008 CE**



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Ancient City of Ur

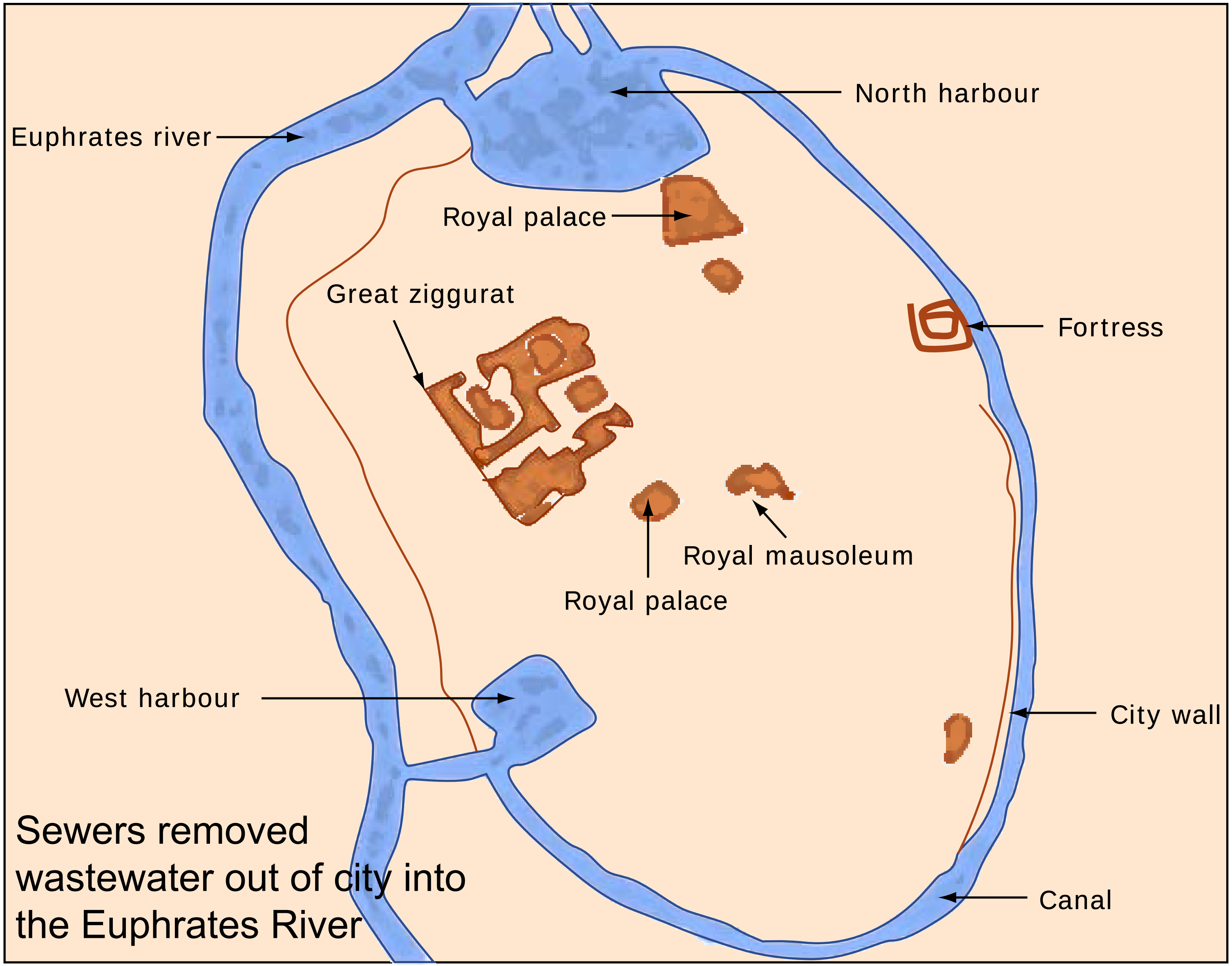


Figure by MIT OpenCourseWare.

Some Major Riverine Civilizations

- Neolithic (ca. 3,500 BCE-1,200 CE)
  - Nile - Egypt (3,500-1,200 BCE)
  - Indus – Mohenjodaro (2,000-1,800 BCE)
  - Tigris, Euphrates – Mesopotamia (5,000-1,600 BCE)
  - Mississippian Cultures - North America (800-1,200 CE)
- Bronze Age (~1,800 BCE)
  - Yellow – Northern China – Banpo
  - Yangtze - Southern China
  - Mekong – Cambodia
  - Red - Annam, Vietnam
  - Salween – Burma (1,200 BCE -1 CE)
  - Amazon – Brazil (1,200 BCE -1 CE)

Mohenjodaro

Ancient Indus River Civilization

Figure by MIT OpenCourseWare.

Mohenjodaro

- Indus Valley Civilization spans Neolithic and Chacolithic cultures
- Commenced c.3,300 BCE and abandoned c.1700 BCE with the first Indo-European (Aryan) raids
- Urban population – may have reached 5 million
- Urban Architecture
- Channeled water and sewerage
- Sedentary, highly stratified population
- Writing system, but undeciphered

Indus River at Mohenjodaro

- Seasonal flooding
- Water management for agriculture
- Irrigation canals
- Public water supply brought via canals from the Indus River
- Gravity-fed supply system
- Great Bath similar to Ghats still used in India today.

India Civilization & Knowledge of Water Treatment

- Heat contaminated water by boiling on fire, heating in the sun, by dipping hot copper into it seven times, cooling in an earthen vessel and also scenting it with flowers of nagkesara, campaka, utpala, patala, etc.
- (The *Susruta Samhita*, Book 1, Chapter 45, Verse 12. – an ancient Indian medical text. 300 C.E.)

Indian Civilization & Knowledge of Water Treatment

According to Buddhist Pali Canon (5th century BCE) one of the “7 requisites” or 7 possessions a Buddhist monk or nun, in addition to a bowl, robes, medicine, was a cloth for filtering water.

Water Management in Ancient China

Note the Yellow River and Yangtze River.

(Map from the CIA World Factbook, https://www.cia.gov/library/publications/the-world-factbook/)

Ancient Huang He (Yellow) River Settlements

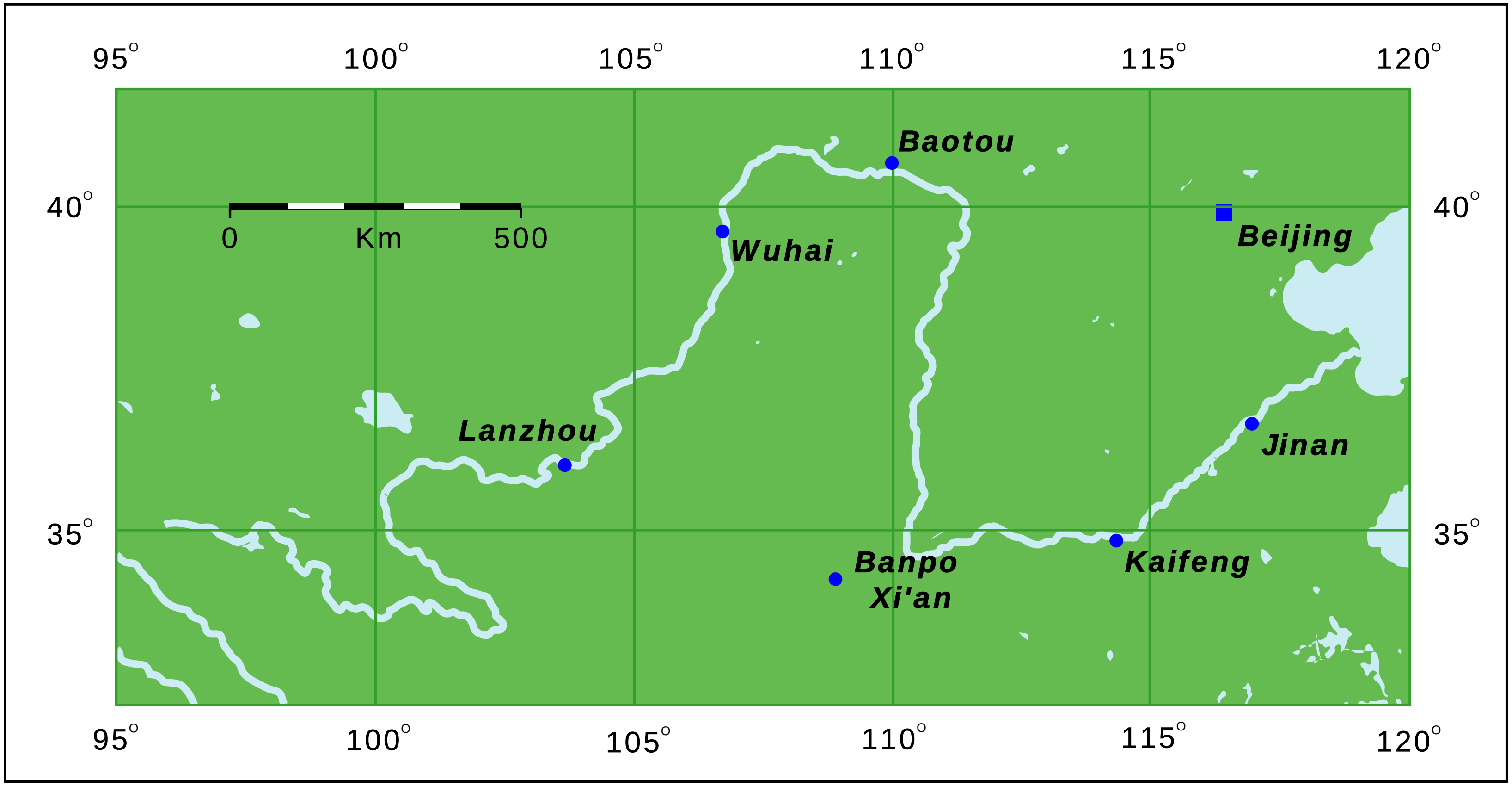


Figure by MIT OpenCourseWare.

Banpo

- Yangshao Neolithic culture, 4800-4200 BCE
- Northeast of Xian, near Yellow River
- Water canals provided irrigation and domestic water for village
- Ceramics used for water collection and storage.
- Possibly a form of primitive written script on ceramics

Channeled Water Supplies

- Kanat/Karez (2,500 BCE- Present)
- Inca (1,200-1,700 CE)
  - Peru, Ecuador
- Maya (800-1,600 CE)
  - Mexico, Guatemala
- Hohokam (800-1,300 CE)
  - South and Central Arizona

Kanat – Karez

Ancient Water Supply and Irrigation System

(2,500 BCE to present)

Cross Section and Plan of Kanat

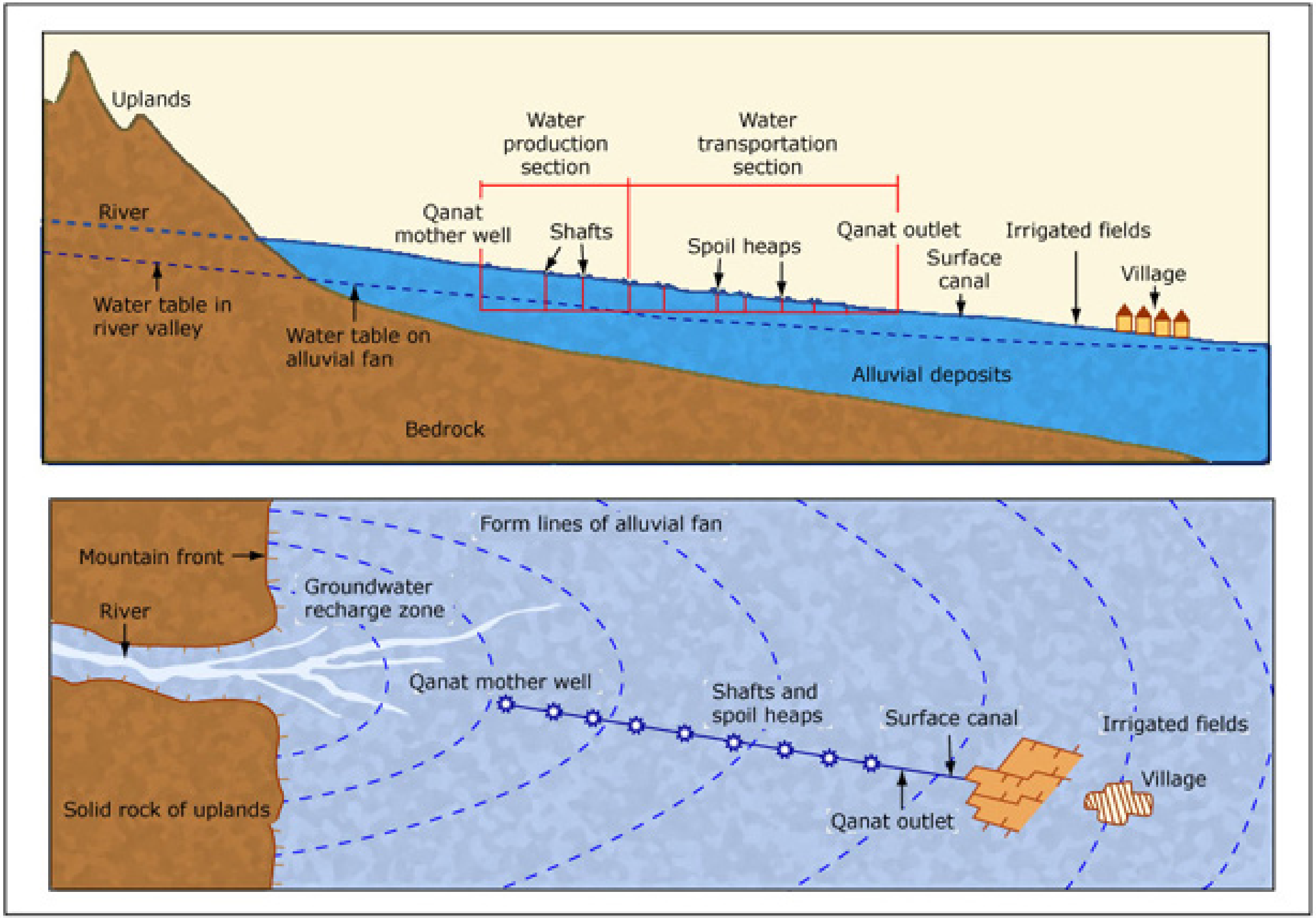


Figure by MIT OpenCourseWare.

Context - Kanat

- Kanat engineering requires sophisticated hydro-geological knowledge!
- Limited seasonal rainfall (at least 4 months with very little precipitation)
- Agrarian village social structure supported public works by its cohesive nature

Map from the CIA World Factbook.

Kanat - Karez Extent

- Origin in Persia (Iran) and Maka (Oman) 2,500 - 2,000 BCE
  - Spread with Islam
- Eastern Trajectory
  - Persia (Iran)
  - Baluchistan (Afghanistan, Pakistan)
  - Xinxiang Autonomous Region, China
- Western Trajectory
  - Algeria, Egypt, Libya, Tunisia, Morocco, Syria, Jordan, Iraq, Saudi Arabia, United Arab Emirates, Italy, Spain
- New World
  - Mexico, Chile, brought by the Spanish

Etymology

- Kanat in Arabic قنات
- Karez in Pashto كاريز
- Qanat (Iran);
- Karez (Afghanistan and Pakistan);
- Kanerjing (China);
- Qanat romani (Jordan and Syria);
- Khettara (Morocco);
- Galeria (Spain);
- Falaj (United Arab Emirates);
- Kahn (Baloch)
- Foggara/ Fughara is the French translation of the Arabic qanat, used in North Africa.

Kanat Hydro geological Engineering System

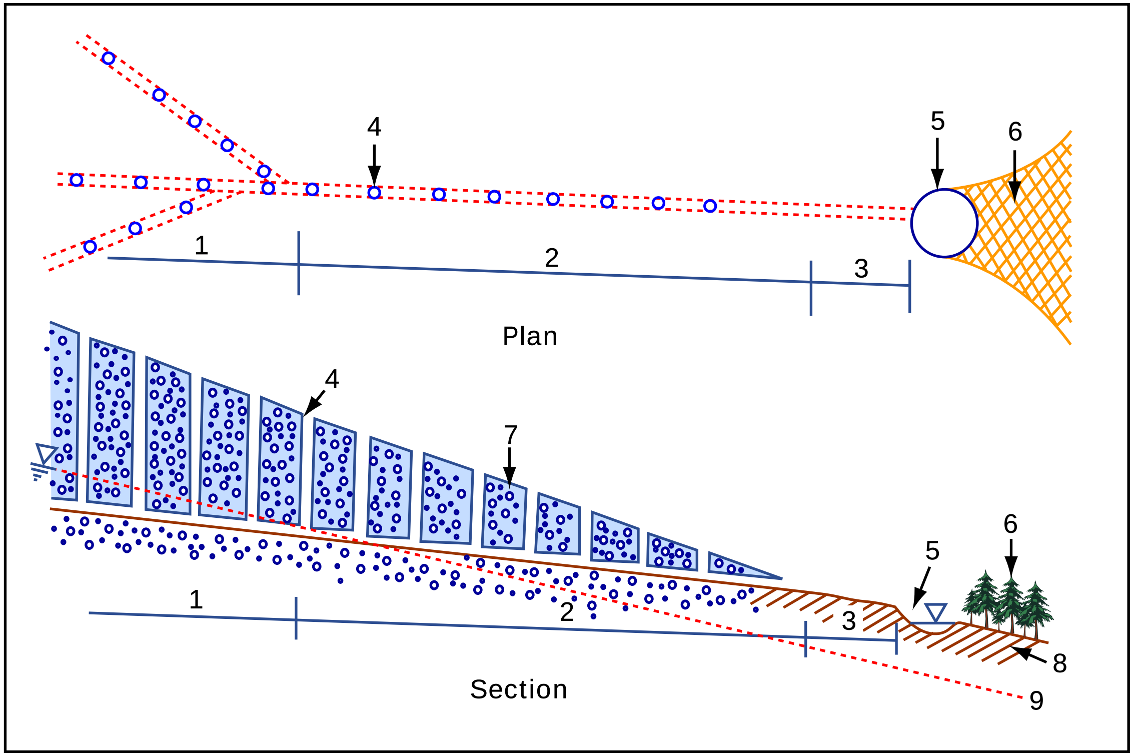


Figure by MIT OpenCourseWare.

Figure 1. General Schematic for a Qanat

(1) Water catchment tunnel
(2) Water conveyance tunnels at slope that enables continuous flow
(3) Open channel as it approaches agricultural fields
(4) Vertical shafts for periodic manual labor cleanout surrounded by donut-shaped piles of annual cleanout silt and rubble
(5) Storage pond for water
(6) Village's tree-lined street and irrigation area

Kanat Outflow – Tuyog, Xinjiang Province, China

- Masonry outflow at the village of Tuyog, Karez Museum, near Turfan
- Karat provided water supply as well as irrigation water

Tuyog Vineyard Irrigated with Kanat Water

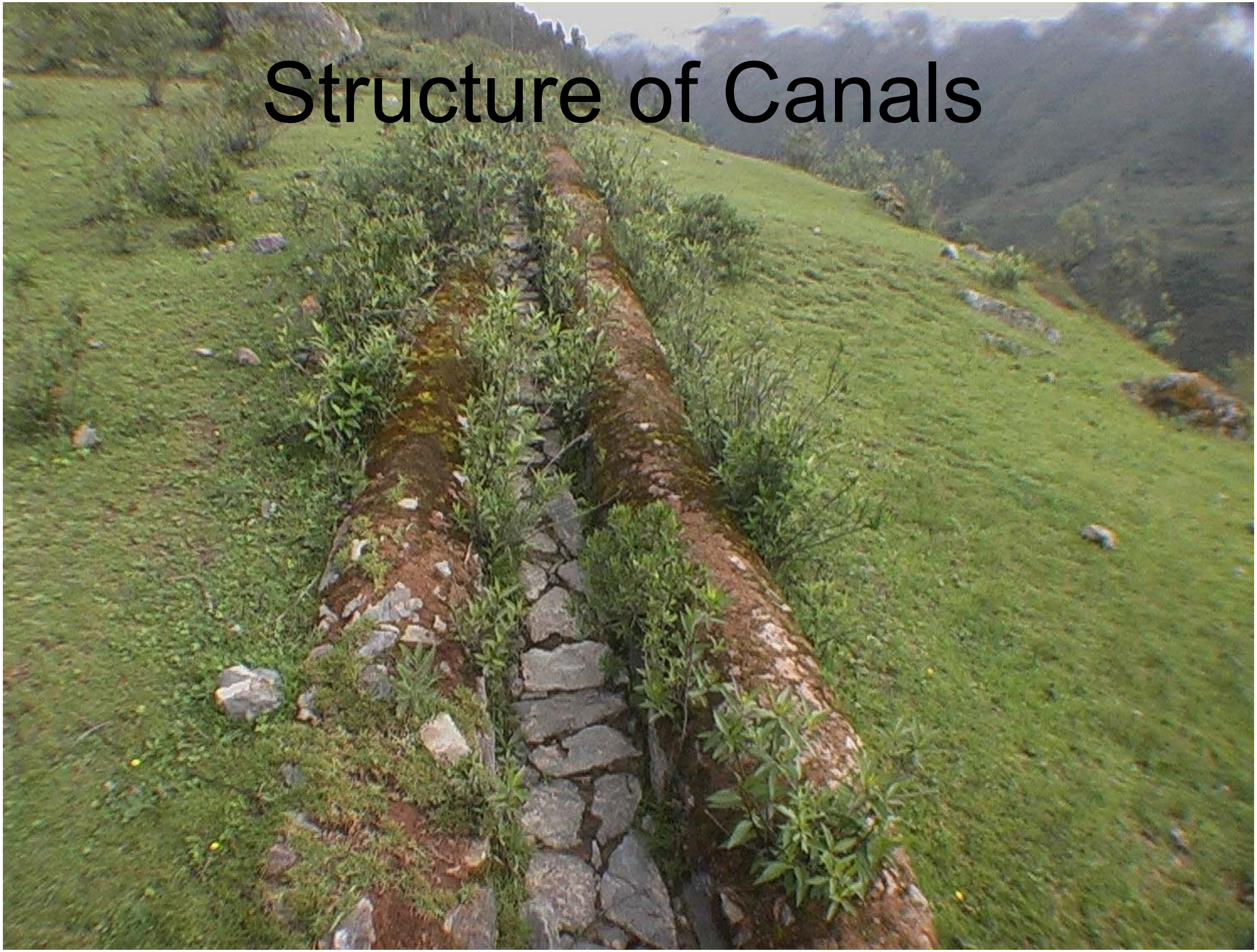
- Irrigation enabled year-round agriculture
- Vineyards especially prized in Kanat villages and towns (grapes dried as raisins)

Inca Canals

Ancient Water Supply and Irrigation System

(1200 to 1700 CE … to present)

Structure of Canals



Canal Structure

- On high gradient (in mountains)
  - Rounded bottom
  - Raised walls
  - Rounded top surface to keep animals off
- On low gradient (near villages)
  - Flat bottom
  - Raised walls
  - Rounded top surface to keep animals off

Inca Settlement – 1450 CE

Archeological site shows terraced agriculture fed by irrigation canals

Inca canals also provided domestic water supply

Roman Aqueducts
and
Sewers

Roman Aqueduct

Instead of drinking polluted Tiber River, water was brought from forest streams in the Apennine Mountains. By 97 AD, Rome had 255 miles of aqueducts. This fresh water was distributed to 144 public latrines, shops and private homes

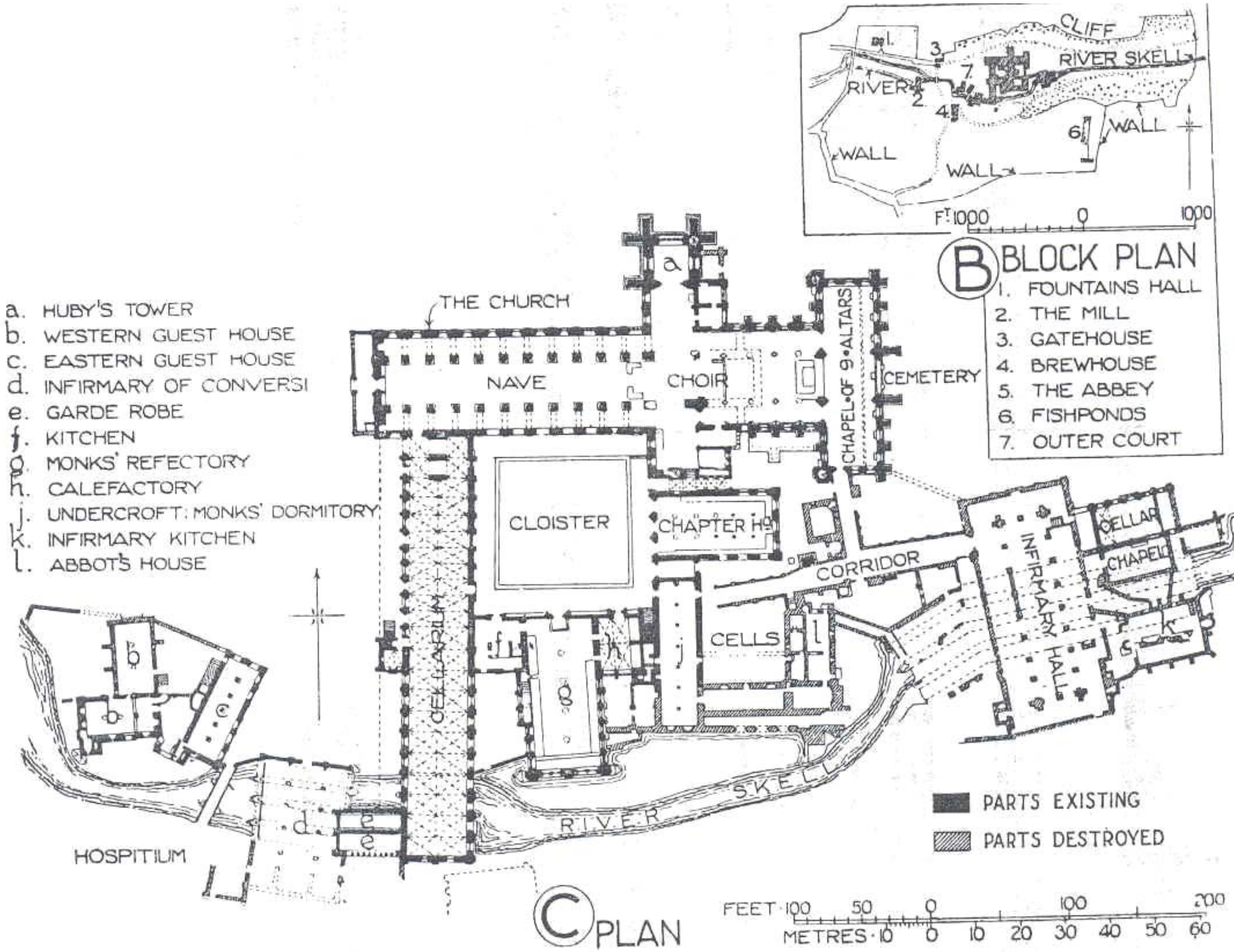
Black and white image of stream removed due to copyright restrictions.

Roman Water Pipes

Middle Ages

- After the Roman empire, Europe "went unwashed for 1,000 years."
- With ascendancy of Christianity, the wealth the Romans had spent on aqueducts and sewers was diverted into cathedrals and Church bureaucracy.
- Ironically, monasteries/convents were among the only places where plumbing was found – they had piped water systems and latrines connected to sewers
- People bought water via carts hauling it from springs outside of cities
- People washed only rarely, with water from contaminated wells.

Plumbing in the Middle Ages



Plan of Fountains Abbey, Yorkshire, 12th–16th century. FROM SIR BANISTER FLETCHER, *A HISTORY OF ARCHITECTURE* (1896)

Beijing, China – mid 16th century

- Part of the genius of the Beijing city plan in the 16th century was its sewer drainage system.
- Beijing City within the wall was 24 sq. miles, yet it contained an underground network of brick sewers 195 miles in total length
- 16th c. Elizabethan London had nothing comparable!
- This drainage system subsequently silted up, but was restored in 1951.

(Needham, J. 1971)

Theories of Disease Transmission

Miasma

"a most subtle, peculiar, insinuating, venomous, deleterious exhalation arising from the maturation of the ferment of the feces of the Earth" (1665)

Contagion

person-to-person transfer

Major 19th Epidemics in Europe and US Cities

- Yellow Fever
- Typhoid
- Cholera

Yellow Fever in Philadelphia

(entered New World in 1647 with slave trade)

<u>1793</u>

- Population = 40,000
- 4,000 dead
- 23,000 fled

<u>1798</u>

- 3,800 dead
- 40,000 fled

Yellow Fever

- Caused by a virus
- Water-related insect vector
- Carried by *Aedes aegypti* mosquitoes,
- Widespread insecticide resistance,
- May be present in other animals, such as monkeys
- Characterized by fever, hemorrhage, and often fatal liver complications
- Safe and effective vaccine exists today
- Currently limited to tropical S. America and Africa, but may re-emerge due to Global Warming.

Typhoid

- Typhoid epidemics were common in the 19th century cities of Europe and America. Most major epidemics of typhoid were caused by pollution of public water supplies
- Caused by the bacteria *Salmonella typhi*
- Transmitted by ingestion of water or food contaminated with feces from an infected person
- Typhoid fever has an insidious onset characterized by fever, headache, constipation, malaise, chills, and myalgia with few clinical features that reliably distinguish it from a variety of other infectious diseases.
- Diarrhea is uncommon, and vomiting is not usually severe. Confusion, delirium, intestinal perforation, and death may occur in severe cases

1780

Paris, France Population 600,000	Philadelphia, PA Population 40,000
Manure: 270,000 m3	**30,000 m3**
Street feces: 81,000 m3	**5,000 m3**
Cesspools: 27,000 m3	**3,000 m3**

In Paris, manure and cesspool waste were all dumped into the Seine River!

New York City Cholera Epidemic, 1832

Drawing of men walking amongst corpses removed due to copyright restrictions.

Cholera entered New World in 1832 via Montreal, reaching NYC in July 1832. By October, 3,500 NYers were dead, and 100,000 fled the city. Construction of NY Croton Aqueduct began shortly thereafter at total cost of $10M

Croton aqueduct and other proposed water sources for New York, 1798 - 1848

Figure by MIT OpenCourseWare.

Cholera

- Until the 19th century, cholera was confined almost exclusively to India, but between 1817 and 1899 successive epidemics spread throughout Asia, Africa, Europe and the Americas.
- The first major advance in controlling cholera occurred in 1854, when the British physician John Snow showed that the outbreak of cholera in a London neighborhood could be traced to drinking contaminated water from a single source, the Broad Street Pump.
- An outbreak in Hamburg, Germany in 1892 was shown to be due to pollution in the Elbe River.

Brief 18th and 19th C. Western Water /Sanitation History

- 1832: First municipal water filtration plant, Paisley, Scotland
- 1851: First International Sanitary Conference, Paris
- 1852: Law passes in London stating that all waters should be filtered.
- 1854: During the terrible London epidemic of 1854, John Snow, by brilliant epidemiological methods, proves cholera to be water-borne.
- 1864: "Report of the Council of Hygiene and Public Health of the Citizens Association of New York upon the Sanitary Condition of the City."
- 1875: Slow sand filters introduced in Massachusetts
- 1883: German scientist, Robert Koch, discovers the bacterial cause of cholera in Egypt.

Cholera

- Cholera (a classic fecal-oral disease)
- Caused by bacteria *Vibrio cholerae,*
- Transmitted by ingestion of contaminated water or food (e.g. shellfish) contaminated with feces from an infected person,
- Cause loose, watery stools, dehydration, and lowered resistance to other infections
- Can kill in hours due to massive dehydration
- Endemic in many parts of world
- Major outbreaks throughout history on all continents.

18th and 19th C. History, continued

- 1880: Louis Pasteur demonstrated the "particulate germ theory of disease," i.e.. that microorganisms cause disease. He was one of the 1st to use vaccination to prevent disease. (Vaccinations were first invented by Africans).
- 1893: Interstate Quarantine Act: U.S. Public Health Service authorized to make regulations necessary to prevent introduction or spread of communicable diseases
- 1895: Coagulation combined with rapid sand filtration in Louisville, Kentucky
- 1900: 3000 water systems in the U.S., However, pumped and piped supplies, when contaminated, provided an efficient vehicle for the transmission of pathogenic microbes to large numbers of people.
- 1903: HazenTheorem – discovery of correlation between contaminated water supply and mortality and that filtration dramatically reduces disease and death from typhoid and other water-related causes.
- 1913: First U.S. drinking water standards

Wooden pipes supplied water to cities such as New York and Boston in the 19th century

Boston

1860
6,500 flush toilets
100 miles of sewers

1885
100,000 flush toilets
226 miles of sewers

TREMONT HOUSE, TREMONT STREET, BOSTON
Photograph by William Halliday, about 1895.

Boston hotels advertised their Victorian Bathrooms as a luxury feature.

Guests at the Tremont Hotel and the Parker House consumed huge amounts water – 25,000 and 20,000 gallons of water per day respectively – at these hotels

Ellen Swallow Richards History (1842 – 1911)

- By the time of her MIT graduation, she was considered a prominent international water scientist.
- Known for her work as a chemist, sanitary engineer, and the founder of home economics – bringing science to the home.
- A "systems thinker" and brought the term "ecology" – into English usage.
- In the spirit of Americans like Benjamin Franklin or Thomas Jefferson, she designed improved systems for ventilation, sanitation and efficiency in her own home, as well as designing urban sanitation systems.
- As a student at MIT, she isolated vanadium and discovered an insoluble residue in the rare ore samarskite.

Ellen Swallow Richards History (1842 – 1911)

- 1868 Enters Vassar as a special student
- 1870 Graduates from Vassar in chemistry.
- 1870 Begins analytic chemical work for the Mass. Board of Health
- 1871 Enters MIT as a special student, age 28. She is one of the first 250 students at MIT. Her request is controversial, but she is admitted without having to pay tuition. At the time she thought this was due to her poor circumstances. In fact, it was to expel her, if it didn't work out. (She later said that had she known this at the time, she would not have accepted).

Ellen Swallow Richards History

- 1873 Receives S.B. degree from MIT. She was the 58th person to receive a MIT degree and the first woman.
- 1873 - 1911 Instructor and chemist at MIT
- After graduation she was 1 of the first 5 "Resident Graduates" (title later changed to Graduate Student). She was not given an advanced degree for her work, apparently because Masters degrees were not given until 1886 and PhDs not given until 1907.
- 1875 Marries Robert Richards, Prof. of Mining Engineering at MIT
- 1876 The MIT Woman's Laboratory opens at the request of the Woman's Education Association of Boston (WEA). "Students in chemistry shall be omitted without regard to sex." This Laboratory enabled secondary school teachers to gain greater competence in scientific laboratory techniques. E.S. developed many of the Standard Methods used for analysis.

Ellen Swallow Richards - History

- 1881 2nd MIT woman graduate (8 years after E. Swallow)
- 1883 All MIT disciplines are open to women
- 1884 Ellen Swallow appointed "Instructor in Sanitary Chemistry" at MIT's sanitary chemistry laboratory under Prof. William Ripley Nichols, a "pioneer sanitarian," and after his death in 1886, under Dr. Thomas M. Drown.
- 1886 Prof. William Nichols dies in Europe, leaving Ellen Swallow a bacteria culture from Robert Koch's laboratory in Germany. Its gelatin mold had liquefied by the time it arrived in the USA, but Ellen, the expert chemist, managed to salvage some of the specimen. She spends extensive time studying the bacteria.

Ellen Swallow Richards - History

- 1887 Massachusetts Statewide Sanitary Survey: MIT's sanitary laboratory (Drown and Swallow) are in charge of the survey, which was executed by Swallow and staff she personally selected, trained, and supervised.
- For nearly 2 years, she analyzed 40,000 samples of the water and sewerage from 83% of the state's population. Swallow's analyses of water samples led to the formation of the Normal Chlorine Map, the standard map for sanitary surveys.
- 1887 MIT Woman's Laboratory transferred to the newly created Marine Biological Laboratory first at Annisquam, later at Woods Hole. Two of the 3 women appointed to the new corporation had been students of Ellen Swallow

Ellen Swallow Richards - History

- *This is an urban age, the age of cities... most of the ills science is called to cure arise from crowded [urban] life." "We need missionaries who will go among the people and show the dense darkness in which they are living."*
- Using statistical methods, she lectured audiences:

  How 16,600 people scattered over 100 miles were likely to lose 282 people to environmental conditions each year. When people were drawn together within fourteen square miles, deaths increased to 415 persons.Concentrated in a one-quarter mile area, 647 or 1 in 25 in the population would die.
- She spoke of the mythical city of Hygeia, where the environment would be improved by Science. She estimated that during each year for five years since 1880, 102,000 lives had been saved in England alone simply by rudimentary environmental improvements.

Ellen Swallow Richards - History

- 1890 Ellen Swallow teaches sanitary engineering, the first course of its kind in any university in the world. The course includes chemistry, bacteriology, engineering, educating the men who went on to design and operate the world's first modern municipal sanitation facilities, research stations, and set up the public health and sanitary engineering departments.
- 1892 E.S. teaches a new course in air quality and analysis.
- 1895 E.S. publishes "The Coloring Matter of Natural Waters, Its Source, Composition, and Quantitative Measurement," a landmark study, quoted up to 1950.
- 1895 - 1890 E.S. suffers professional and personal disappointments. Her "Oekology," an interdisciplinary science, is not gaining support from the specialized scientific aristocracy.
- 1900 MIT has 58 women graduates in 6 disciplines

Ellen Swallow Richards Legacy

- Hiram Mills, Boston politician who put the recommendations of the Sanitary Survey into effect became known as the "Father of Modern Sanitation."
- Allen Hazen ran the Lawrence Livermore Experimental Station (at recommendation of ES)
- Edwin Jordan credited as the 1st to study the process of nitrification, but the 1st seminal paper is by Jordan and Swallow.
- Thomas Drown, who later became president of Lehigh University, got credit for the Mass. State Sanitary Survey
- William Sedgwick, the biologist who learned microbiology from E.S., a professor at MIT, who went on to found Harvard's School of Public Health and became known as the "Father of Public Health" and of the discipline of environmental engineering, spoke of Ellen Swallow Richards, in his 1911 eulogy, as his "great teacher."

MIT Sanitary Engineering – Old Course 11

- 1865: MIT founded. One of its first curricula was in Civil Engineering (designated at the time as Course II).
- 1889: William Sedgwick helped to organize what became Course XI, Sanitary Engineering,
- 1892: Course XI was assigned to the Civil Engineering Department for administration (which by then was designated Course I).
- 1944: all of the undergraduate courses in Course XI, sanitary engineering, were eliminated and graduate courses in sanitary engineering were combined with the graduate courses in Public Health Engineering.

MIT Sanitary Engineering – Old Course 11

- After WWII, MIT wanted to build up its research, and brought in William Stanley to head the new graduate program in sanitary engineering. Stanley hired Clair Sawyer, Murry Horwood, A. A. Thomas,and Rolf Eliassen, and with the establishment of the "William Sedgwick Memorial Laboratories in Sanitary Science," a vibrant research program was reestablished.
- In 1950, Thomas left to practice engineering,and Horwood retired. Ross McKinney, who received his Sc.D. under Horwood, was asked to stay on as a faculty member. In 1958 Stanley retired and Jim Symons, who was getting his Sc.D. with McKinney, was asked to stay on. In that same year, Clair Sawyer left to join Metcalf & Eddy.
- Thus in 1959 the program had Rolf Eliassen, Ross McKinney, and two junior professors, Perry McCarty (who was getting his Sc.D. with Ross McKinney) and Jim Symons. Funding was strong and there was optimism that the program would survive.

MIT Sanitary Engineering – Old Course 11

- 1959: The support for sanitary engineering was tenuous, A major reorganization of MIT which stressed research and mathematical modeling was a final blow to Course XI.
- Early 1960s: the decision by MIT to close down its sanitary engineering (Course XI) resulted in an explosion that sent some of our very best sanitary engineers in the world to other universities, to establish their own centers of excellence.
- Russ McKinney was the first to see opportunities elsewhere, and decided to take a position at the University of Kansas.

MIT Sanitary Engineering – Old Course 11

- Rolf Eliassen moved to Stanford University which had made him a standing offer, and he convinced Perry McCarty to move with him.
- Jim Symons went to the U.S. Public Health Service Laboratories in Cincinnati and in 1982 to the University Houston.
- 1992: MIT realized its mistake and reestablished environmental engineering (nee sanitary engineering) as a part of Civil Engineering.
- 1992- department renamed Civil and Environmental Engineering. It provided the seeds that populated some of the best environmental engineering programs in the nation.

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