Brown AND Caldwell

Great Caesar's Ghost

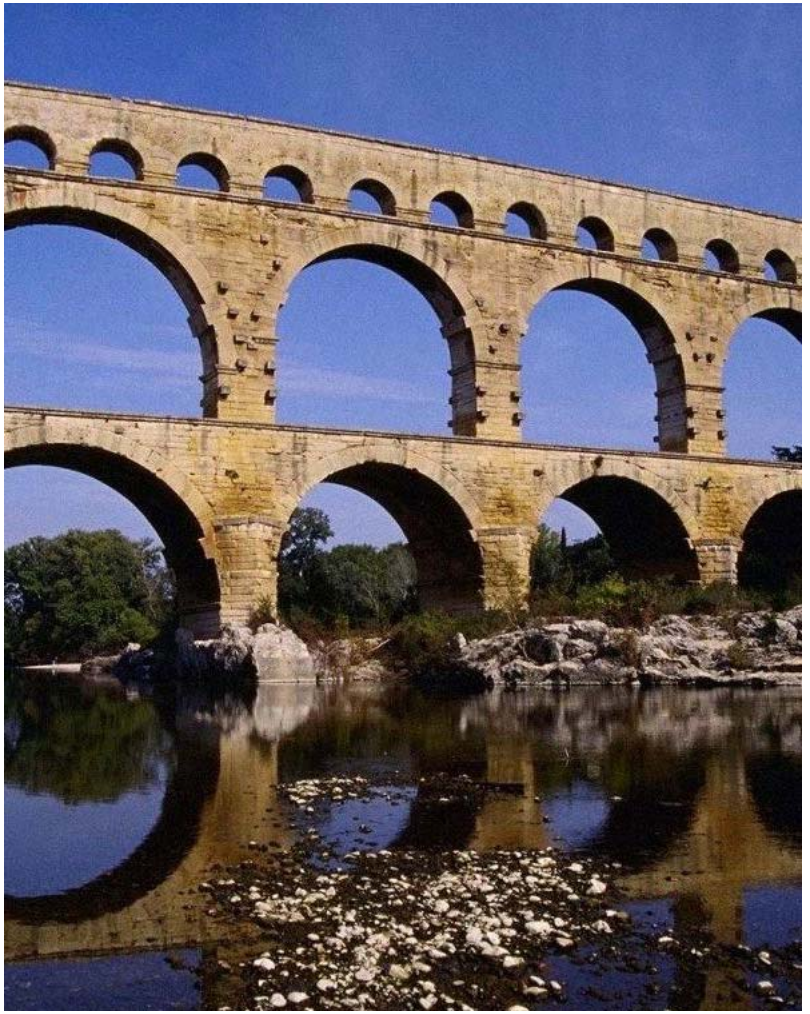
How Water Supply Management Issues Have Changed from 97 AD to Now

Outline ❯

- Background
- Who was Frontinus?
- Ancient Rome's Water System
  - Description
  - Management principles
- What Frontinus Accomplished
- **Relevance:** What Can We Learn from Ancient History?

Historical Background (Way Back!)

- Ancient Roman Water Supply System
  - One million inhabitants
  - Water demand 84-300 mgd
- Famous Commissioner: Sextus Iulius Frontinus
- Developed the Foundations of Modern Water System Management



Who Was Frontinus?

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Sextus Iulius Frontinus

- 40-103 AD
- Army General
- Engineer
- Writer
- *Curator Aquarum Urbis Romae*
  (Water commissioner of the City of Rome)

Served Under Three Administrations

Emperors

Titus Flavius Caesar Domitianus Augustus

- Domitian
- Reigned 81-96 AD
- Ruthless, efficient autocrat-assassinated

Marcus Cocceius Nerva

- Nerva
- Reigned 96-98 AD
- First of the “5” good emperors
- Both his grandfathers served as water commissioner

Marcus Ulpius Traianus

- Trajan
- Reigned 98-117 AD
- Nerva’s adopted son

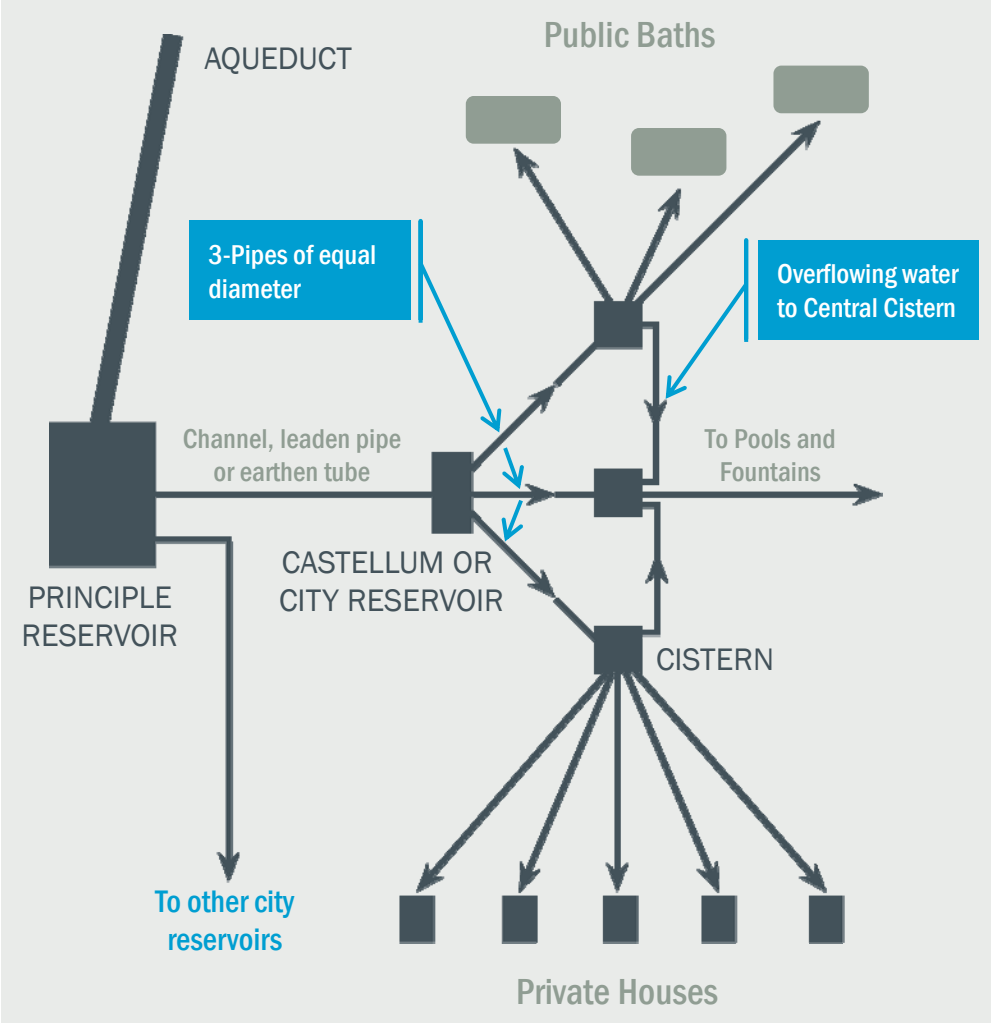
Politically Astute Commissioner

Knew which side of his lentaculum bread was buttered

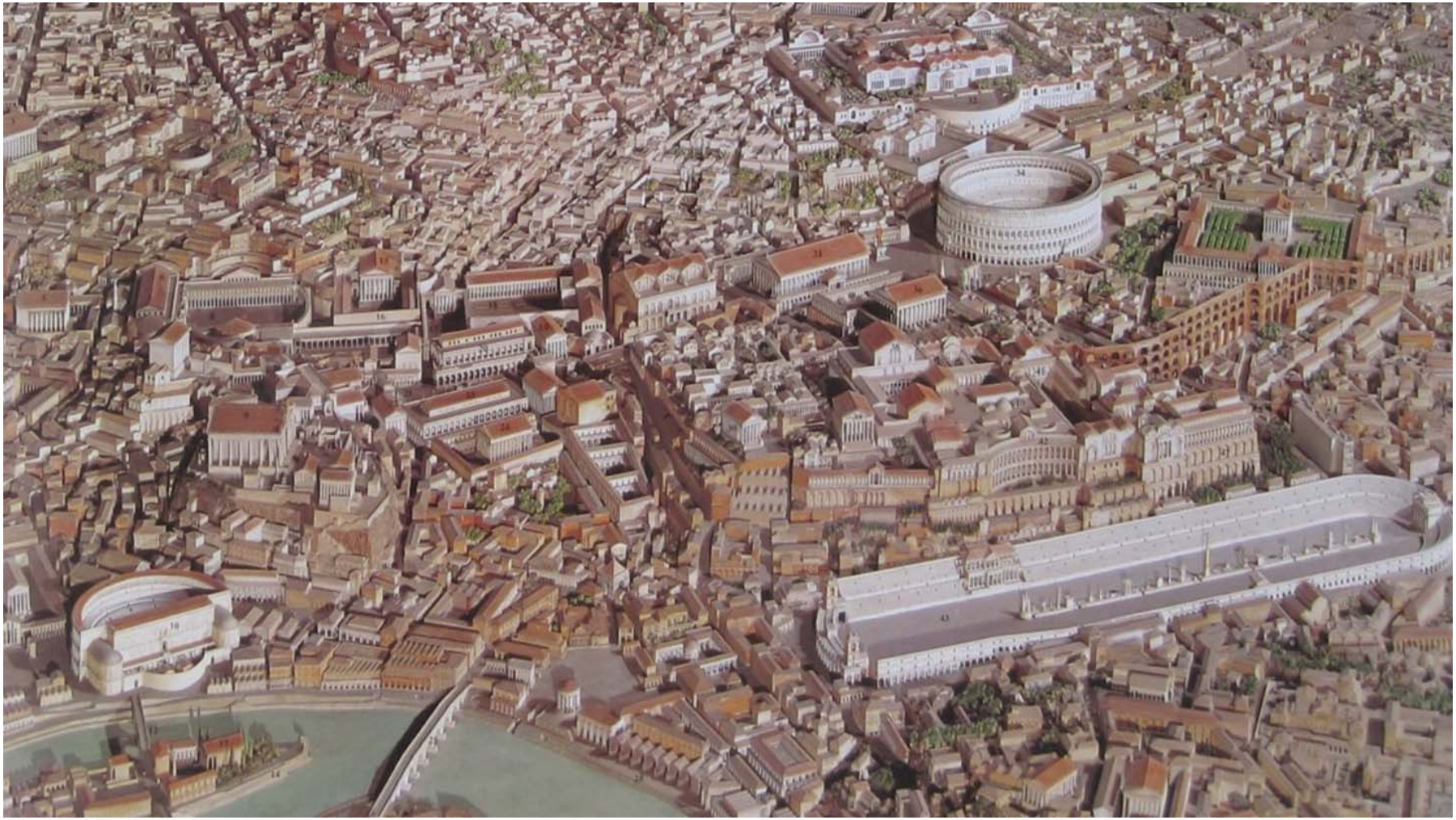
Ancient Rome's Water System

Elements of Ancient Rome's Water System

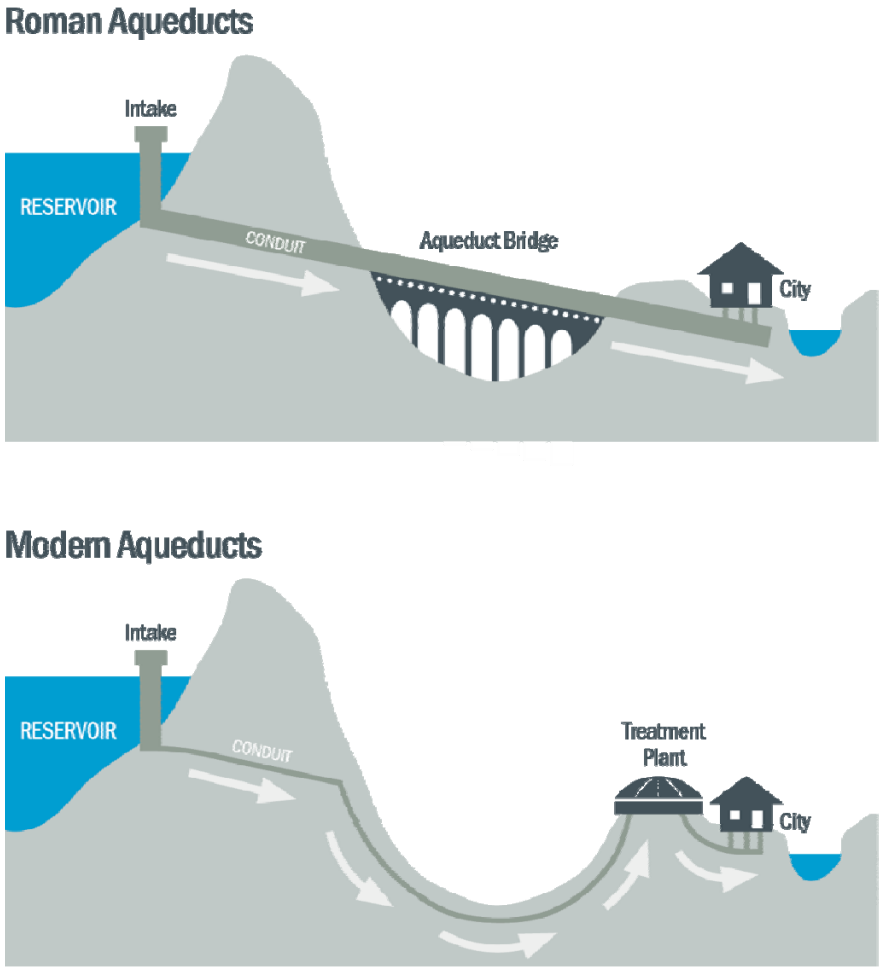
- Source Development
- Aqueducts
- Principal Reservoirs
- Treatment Systems
- Piping
  - Transmission
  - Distribution
- City Reservoirs *(Castella)*
- Service Connections (*calices*)
- Cisterns
- Typical Uses
  - Public Baths
  - Fountains
  - Pools
  - Private houses



Depiction of Rome Water System

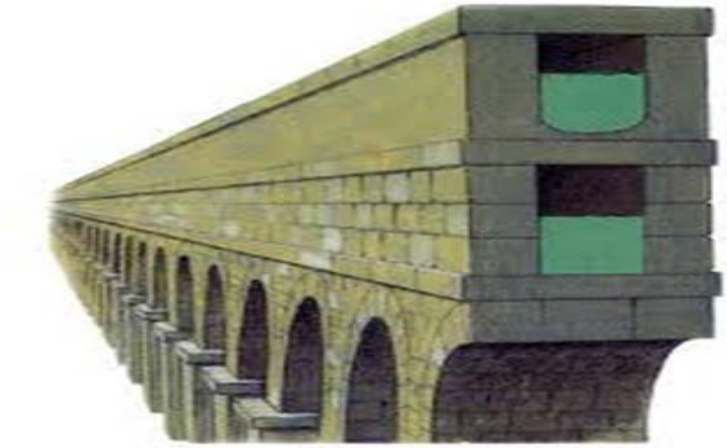


Aqueducts-General Arrangements



Aqueducts and Supporting Structures

Cross Section Views of Aqueducts



Close-Ups of Aqueducts

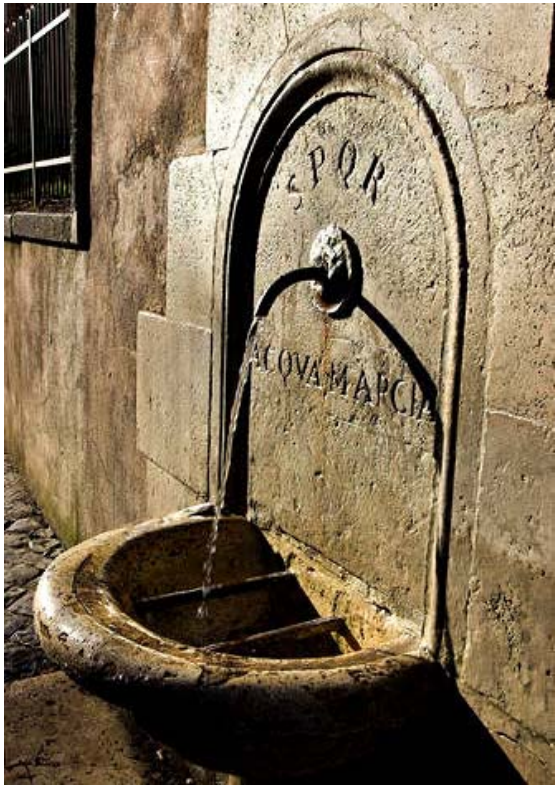
Castella

Large Cisterns

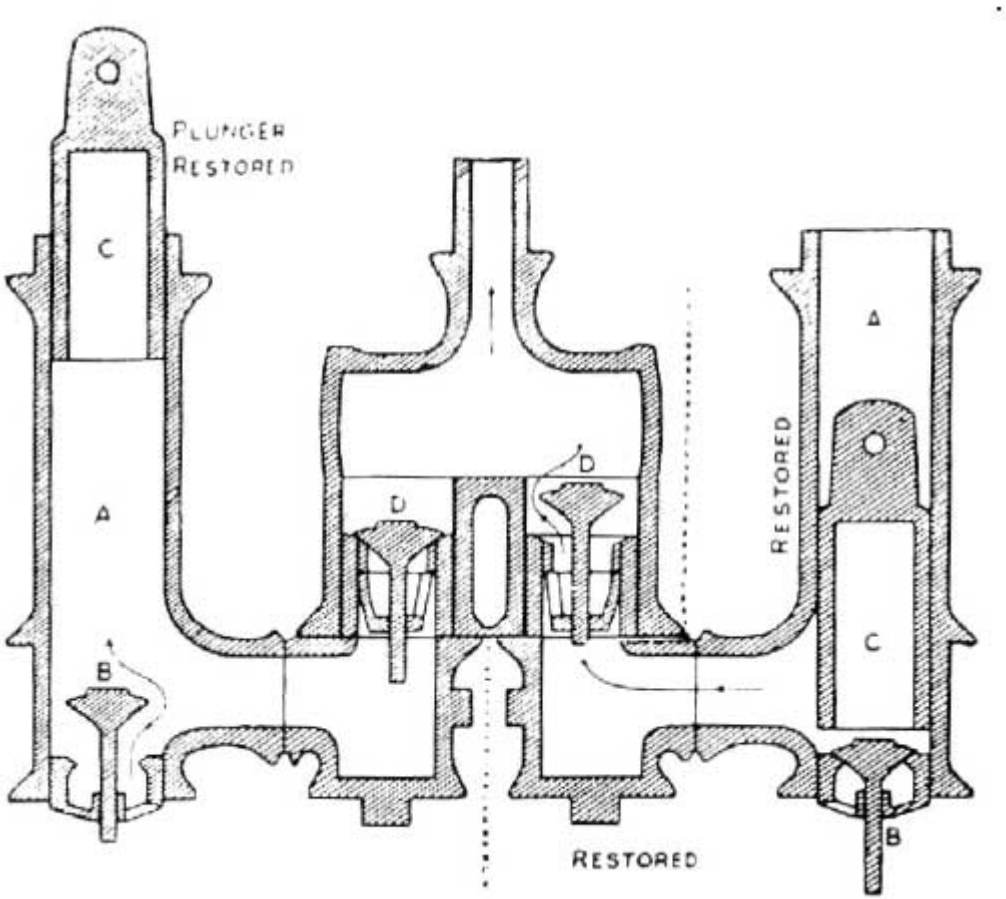
Small Cisterns

Public Baths

Fountains



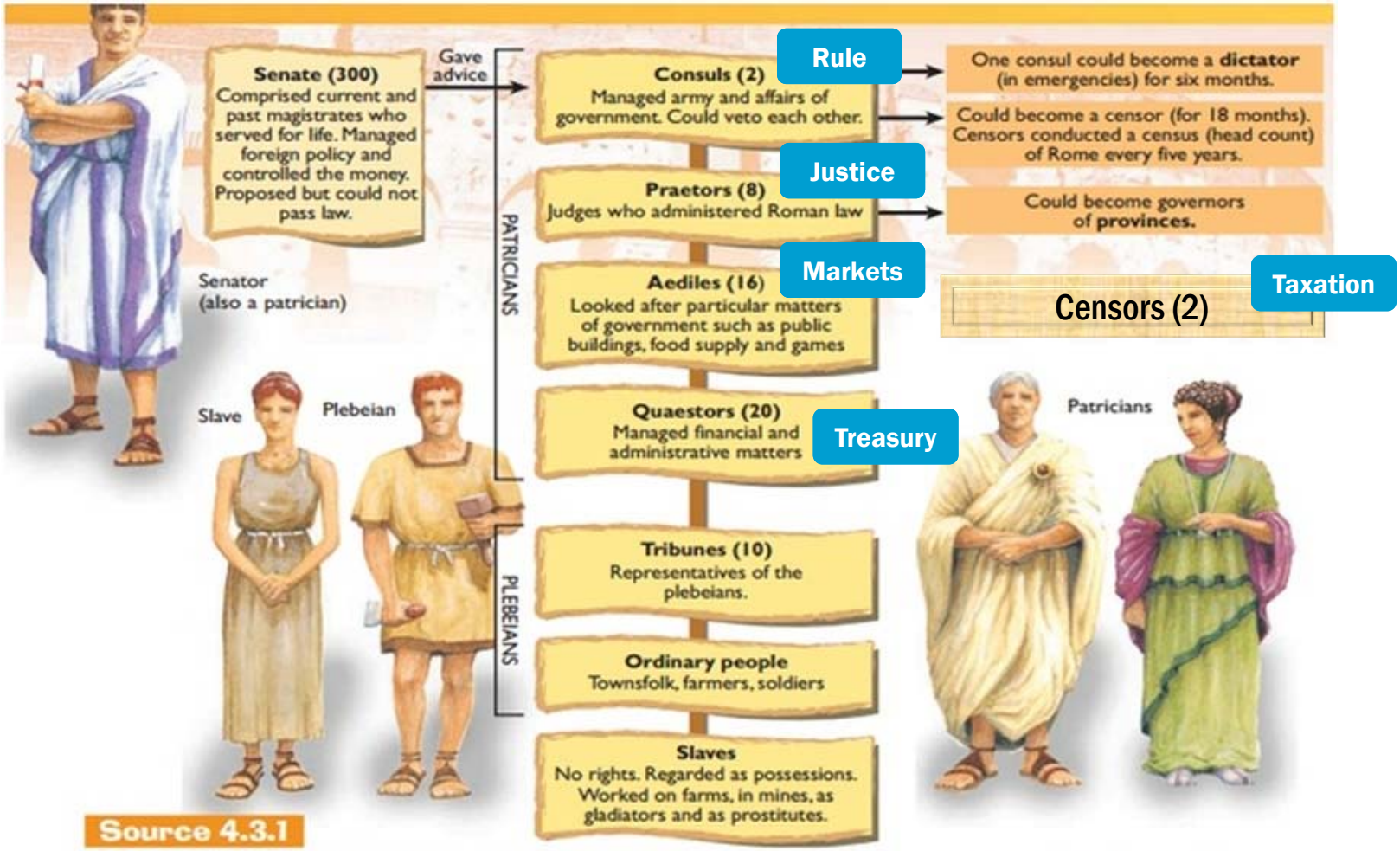
Roman Double Acting Plunger Pump



A.G. Drachmann, Ktesibios, Philon, and Heron: A Study in Ancient Pneumatics (1948), and The Mechanical Technology of Greek and Roman Antiquity (1963).

Organizational Structure

Structure of Government
Senatus Populusque Romanus

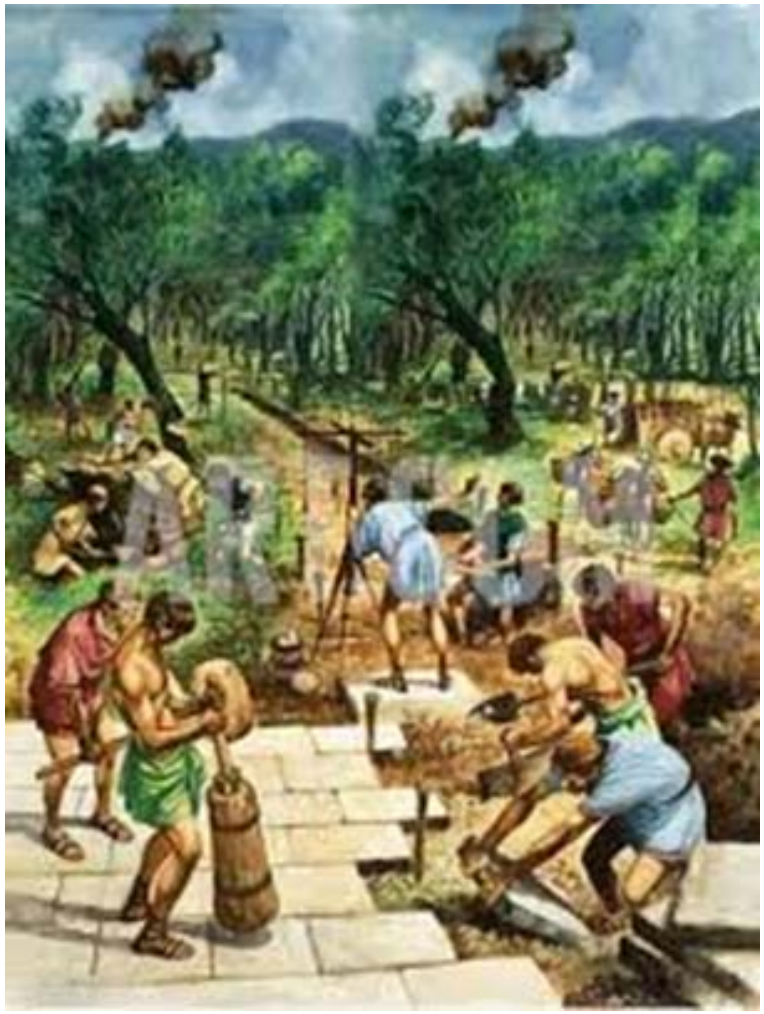


Source 4.3.1

The structure of the Roman Republic, c.80 BC. Elected officials were those from the quaestors upwards on the cursus honorum.

Structure of Water Department-*Statio Aquarum*

- Water Commissioner (*Curator Aquarum*)
- Chief Engineer
- Deputy Commissioner (*procurator*)
- Architects (later known as hydraulic architects)
- Civil engineers
- Military engineers
- Secretaries
- Two military policemen (*lictors*)
- Slaves
  - Foremen
  - Water Registrar
  - Levelers
  - Notebook keepers
  - Reservoir keepers
  - Pavers
  - Line walkers
  - Plasterers

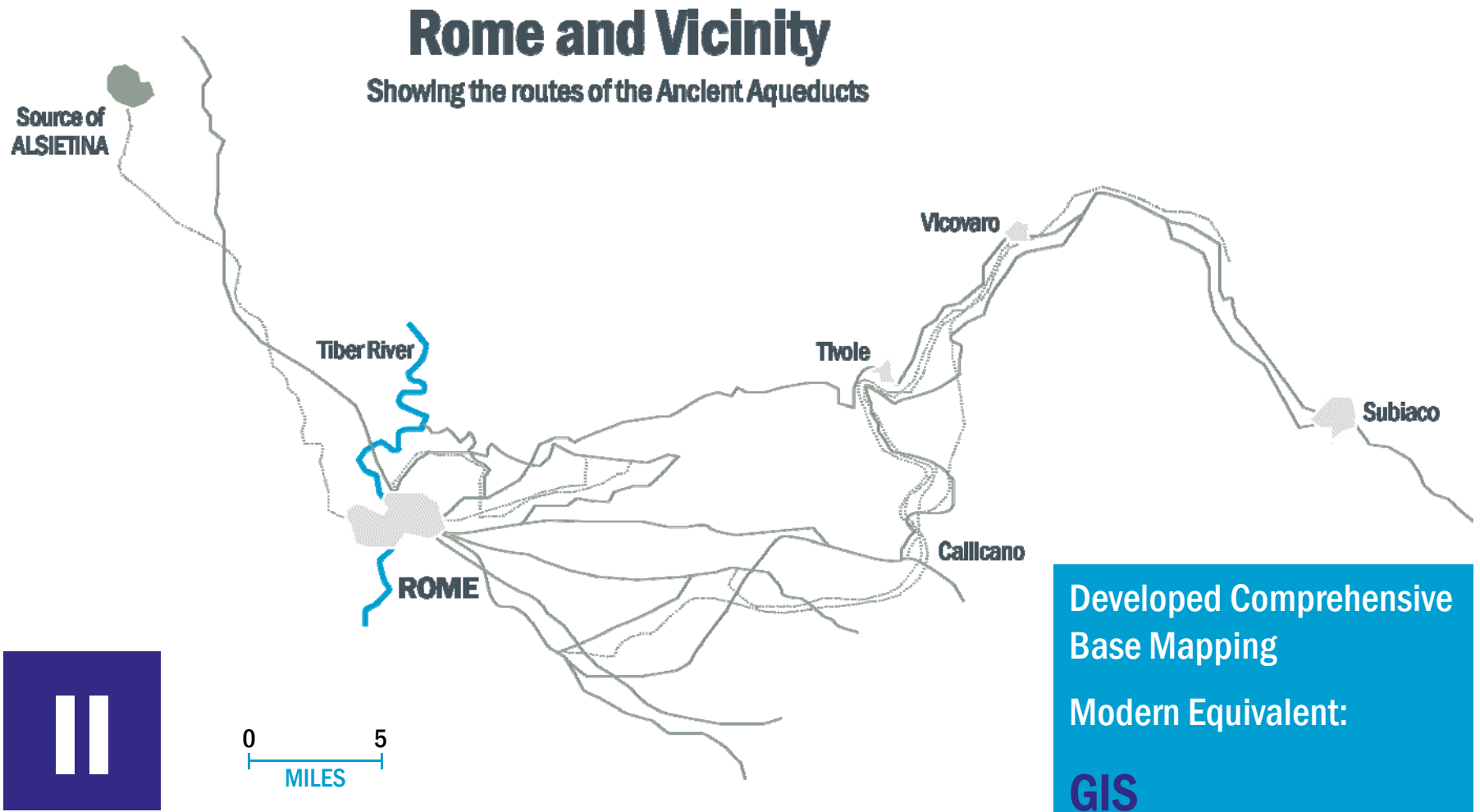


What Frontinus Accomplished

Frontinus Approach to Water System Management

- Source Document
  - *De Aquaeductu Urbis Romae,* circa 97 AD
- Lays out Principles of Modern Water System Management Practices
- "*Collecting facts…arranging them in an orderly manner and…into a systematic body*"
- "*This booklet…is…a… reference manual for administrative purposes*"

Overall Water System Map



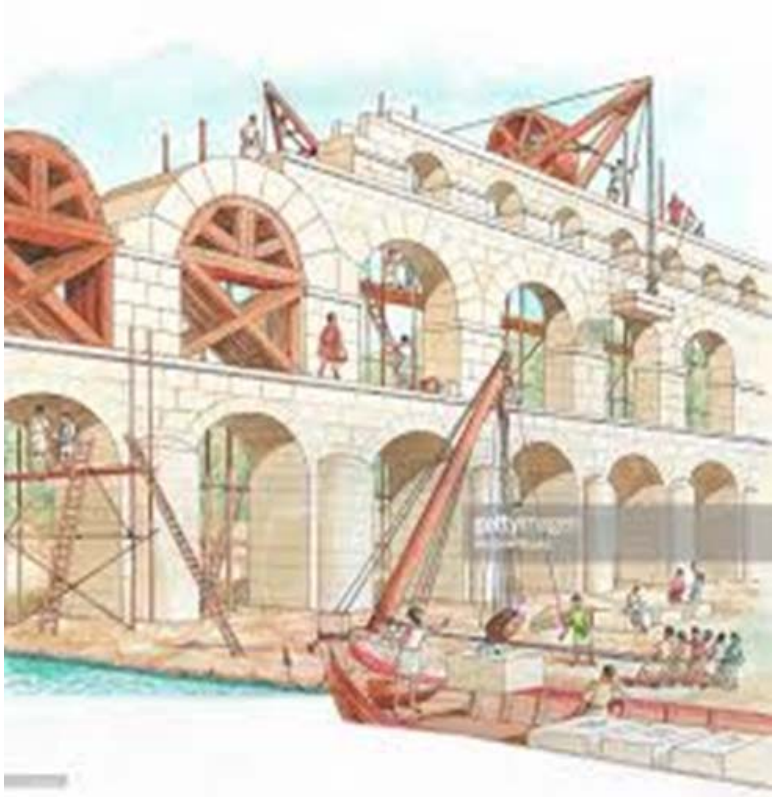
Developed Comprehensive Base Mapping

Modern Equivalent:

GIS

Frontinus Detailed Facilities Inventory

- First Aqueduct (Aqua Appia) 312 BC
- Aqueducts
- Deliveries
- Elevation drop: 800 feet
- Elevated Water Storage tanks: 247
- Varying pressure zones
- Preferred slopes not less than 0.5%



Modern Equivalent:
Hydraulic Network Modeling

Summary of 11 Major Aqueducts

Aqueduct	Construction Complete	Volume (mgd)	Length, miles	Water Source & Quality	Notes
Appia	312 B.C.	20	10	Springs/Good	All undergound except inside walls, 70% for civic/imperial uses
Anio Vetus	272-269 B.C.	48	40	River/Poor	Used for baths, gardens, industry
Marcia	144-140 B.C.	50	56	Spring/Best	Pure/cold/hard water, Antoniniana branch supplies baths of Caracalla, used to 10th c.
Tepula	126-125 B.C.	5	11	Streams/Good	Warm water (60F), abandoned in 33 B.C. by Agrippa, combined water with Julia
Julia	33 B.C.	13	14	Springs/Good	Agrippa combined Tepula with this water
Virgo	22-19 B.C.	27	14	Marsh/Good	Supplied Agrippa's baths, almost all underground, many sources along channel
Alsietina	2 B.C.	5	14	Lake/Poor	Built to supply Augustus' Naumachia (basin for mock sea battles)
Claudia	A.D. 38-52	49	43	Springs/Good	Several Branches built later in the city
Anio Novus	A.D. 38-52	50	54	River/Okay	Poor until Trajan improved the source
Traiana	A.D. 109	30	35	Springs/Good	Built after Frontinus writings
Alexandrina	A.D. 226	6	14	Springs/Good	Served baths of Alexander Severus
Total		303	305		

Frontinus Identified Flow Disparities

- "*I lost no time in devoting myself to a probing audit*"
- Found Great Disparities in Flow

12,755 ***quinariae*** **(140 mgd)** → **14,018** ***quinariae*** **(153 mgd)**
OFFICIAL SUPPLY — **RECORDED DELIVERIES**

22,800 ***quinariae*** **(250 mgd)**
ACTUAL SUPPLY as Measured by Frontinus

He Nearly Doubled the Official Supply!

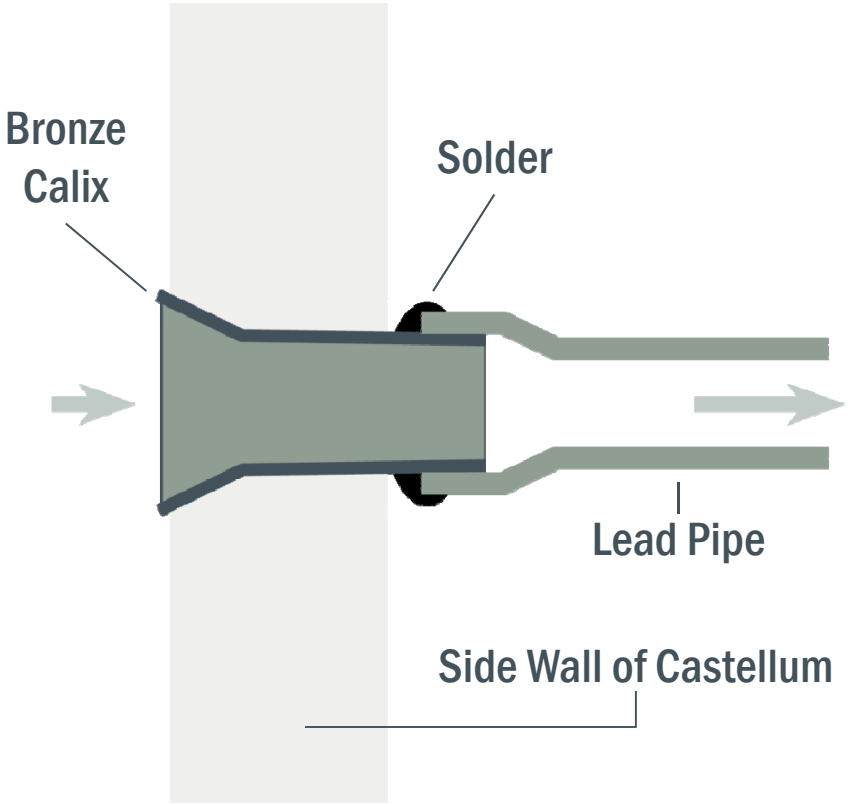
Causes

- "*When, however, the facts disclose a smaller quantity in the pipe used for delivery, but a surplus in the receipts, it is plain that we are dealing not with error, but with fraud*"

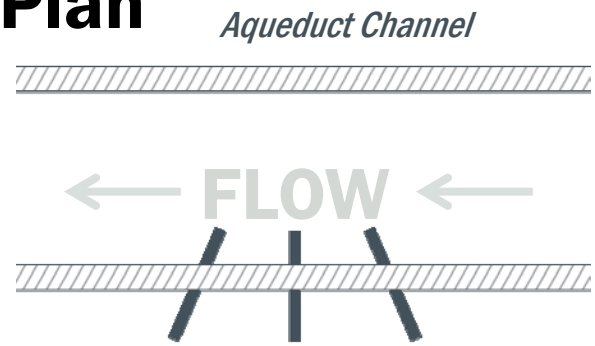
Modern Equivalent:
Water Balance, Accounting , and Best Business Practices

Water Control and Distribution Systems

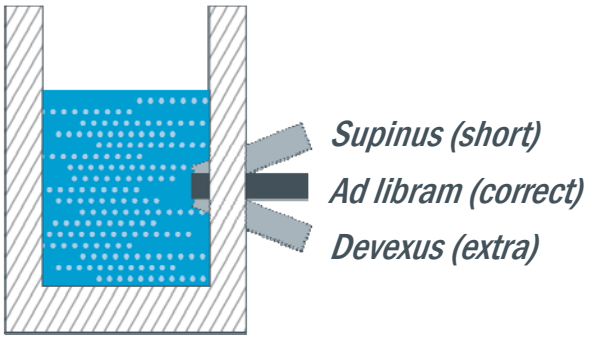
Calix - A Regulating Orifice



A. Plan



B. Section



Calix Used for Flow Regulation

- Only allowed to tap water from Delivery Tank
  - "*Water is to be drawn only from a delivery tank, so that neither the channels nor public pipes may be damaged by numerous tappings*".

- Orifice Control (plus 50 feet of lead pipe) by Senate Resolution
- Made of bronze to deter cheating
- Lessee's Name Stamped by Officials (both calix and lead pipe)
- Lots of cheating revealed

Modern Equivalent:

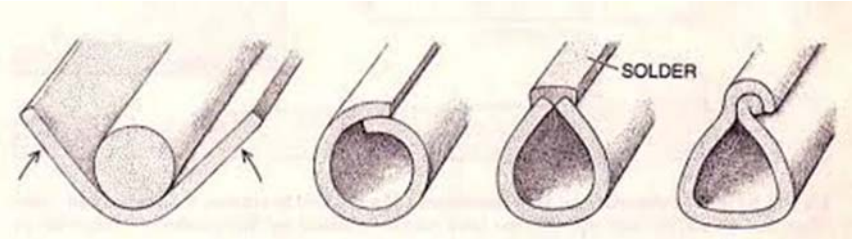
Water Meters, Control of Unaccounted for Water

Background: Linear Units of Measure

- *Milia* (mile) = 1,000 paces (*milia passuum*)
- *Passus* (pace) ≈ 4’-10” (English units)
- *Pedis* (foot) ≈ 0.97 feet (English units)
- *Uncia* (inch) = 1/12 *pedis* ≈ 1” (English units)
- *Digitus* (digit) = 1/16 *pedis* ≈ ¾” (English units)
- *Quinaria* = Diameter of smallest standard lead pipe
  = 5/4 digits

Developed Basic Piping Standards

- Established Standard Pipe Sizes Based on Diameter
  - The “5-pipe” (*quinaria*)
    - Diameter: 5/4 digits
    - Flow Capacity: Defined as 1 *quinaria*
    - Made from rolled lead sheets



- Estimated Flows Based on Pipe Diameter

Lead Distribution Pipes

Standard Dimensions for 25 Pipes Based on Two Gages (Only 15 in Common Use)

Pipe Name	Diameter, digits	Diameter, inches (English)	Area, digits^2	Flow Capacity, quinariae	Est. Flow Capacity, gpm
5-pipe	5/4	0.9	1.2	1	7.6
6	6/4	1.1	1.8	1-113/144	14
10	10/4	1.8	4.9	4	30
20	20/4	3.6	20	16-7/24	120
25	5-185/288	4.1	25	20-35/96	150
40	7-13/96	5.2	40	32-7/12	250
120*	12-17/48	9.0	120	97-3/4	740

* *Frontinus "corrected" the dimensions used by aquarii (water-men)*

Modern Equivalent:

AWWA and ASTM Pipe Standards

Water Supply Resiliency

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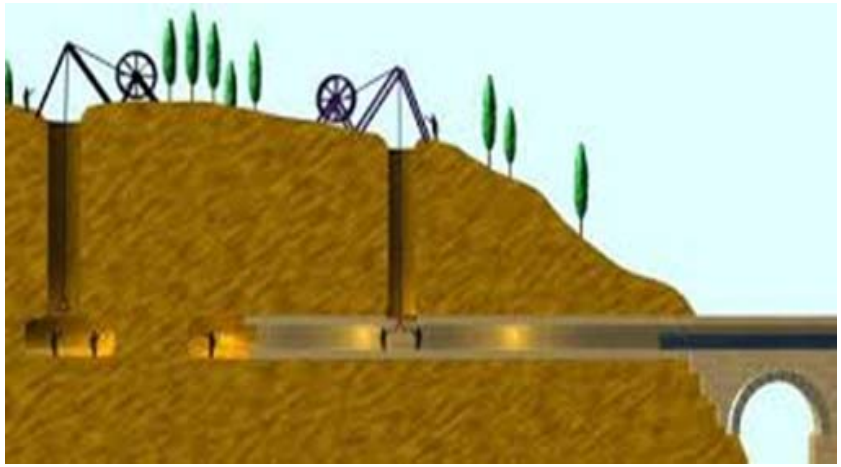
Attention to Reliability

- Buried sections of the Marcia aqueduct for protection against "*hostile interruption*"
- Abandoned some buried aqueducts "*beyond repair*" and replaced with above ground structures
- Major buried aqueducts included periodic inspection shafts
- 2 maintenance crews, one for emergencies



Redundancy Via Multiple Sources

- Developed additional sources to deal with drought
- Looping
- Constant tank overflows used to improve public health and aesthetics

Modern Equivalent:
Vulnerability and Sustainability Studies

Water Quality

Typical Water Quality Concerns

- Concerns of "*purity and palatability*"
- High hardness typical
- Knew of lead pipe health risks (Vitruvius - earlier commissioner)

Water Quality Management Strategies-1

- Watershed Protection

- Blending

Water Quality Management Strategies-2

- Source Separation and Use of Lesser Quality Water
  - Covered critical intakes
  - Frontinus repurposed supply sources
  - Identified lesser quality sources

Water Quality Testing Standards

- Water Quality Considered Adequate if:
  - *"Spring is limpid and transparent"*
  - Vegetables cooked well (relatively soft)
  - No deposits in vessels
  - Leaves no stain in a Corinthian vessel made of good bronze
  - No taste or odor
  - If "*inhabitants…are strongly formed, of fresh color, with sound legs, and without blear eyes, the supply is of good quality*:"
    - Early epidemiology!

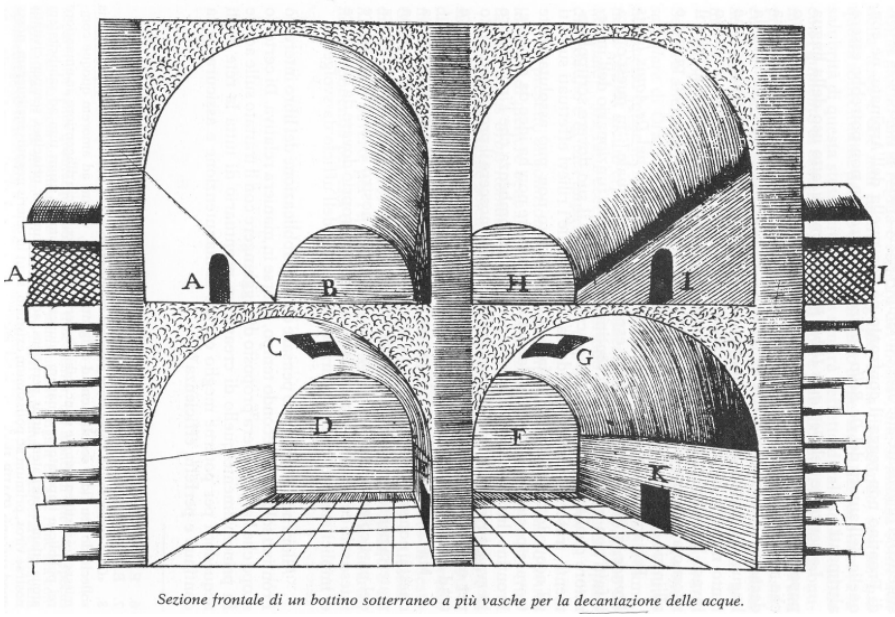
Modern Equivalent:
Standard Methods

Water Treatment Approaches

- Covered aqueducts
- Treatment for "*turbid and muddy water*"
  - Covered settling tanks
  - High quality tributary (Herculean Brook) is degraded by other streams, "*but by admixture it loses the charm of its purity*"
  - Multiple settling tanks in series
  - Filtration

Settling Tank Design

- Cross-section of the multi chamber settling tank in the Aqua Virgo as drawn by Raffaello Fabretti.
  - A. Inlet to the first chamber B.
  - C. Opening to the second chamber D.
  - E. Opening to the third chamber F.
  - G. Opening to the fourth chamber H and outlet I
  - K. (Sluice) gate to discharge impurities into a sewer



Sezione frontale di un bottino sotterraneo a più vasche per la decantazione delle acque.

Treatment Systems

Flow-through Gravity Filters (amphorae) Filled with Charcoal, Sand, and Gravel Neopolis, Spain

Modern Equivalent:

EPA and the 1974 Safe Drinking Water Act

Water Quality Violations

- *"No one with wrongful deceit is to defile with excrement water which issues for public use. If any person should so defile, the fine is to be 10,000 sesterces"* *(in the vicinity of $100,000 dollars)*

Modern Equivalent:

State Fines

Maintenance and Repair

Maintenance

- Aqueduct Damage
- Customarily Awarded by Contract
- Senate resolution to Pay Adjacent Landowners

Frontinus Changed Maintenance Procedures

- Controlled work crews used illegally in private construction
- Assigned work to crews a day in advance
- Required records be kept of daily accomplishments
- Crews paid from state treasury, offset by revenues collected from customers
- Restored lost revenue (250,000 sesterces) diverted to "*other accounts*"

Frontinus Prioritized Maintenance and Repair

- "*Subterranean portions, protected from exposures to extremes of cold or heat are less liable to suffer harm*"
- Repair damage without interrupting flow and build temporary structures and continuous channels formed by leaden troughs.
- Avoid repairs in aqueduct interiors in summer

- Repair one aqueduct at a time
- Concrete work to be done between April 1 and November 1

IV

Modern Equivalent:

Risk ranking prioritization, asset management principles, Capacity Management, Operation, and Maintenance (CMOM) Programs

Legal Foundations

Legal Foundation for the Welfare of the Water System

- Established by Statute, Senate Resolutions, and Emperor Policies, especially during reign of Augustus
- Judicial authority given by the state to two local men in each district

- Senate Resolution: Authority given to water commissioners when travelling outside the city on business

Water Allocations and Grants

- Commissioner "*will need to be specially watchful to counter various and shifting forms of fraud*"
- Inconsistent water grants given by civil authorities (censors and aediles)
- Some water granted for delivery "*into the homes of leading men of the state*"

Water Rights

- Submit official application
- Obtain written authority from the Emperor
- Quantity limited by grant
- Administrative authority by appointed imperial deputy

Modern Equivalent:

Water Rights Law

Water Grant Renewals

- Grant to be renewed whenever the occupant changes—not passed down to heirs or new property owners
  - Syndicate rights apply until last syndicate member gives up interest
  - Exception: public baths "*water once granted should remain theirs forever*"
  - Vacant water rights to be made known immediately
    - 30 day grace period before expired water is cutoff

Use of Lapsed Water

- Use of Lapsed Water- water that overflows basins and fountains

- "*Properties which had been irrigated with public water against the law were confiscated*"

VII

Legal Recourse for the Welfare of the Water System

- Senate resolution for easement to keep buildings and trees away from the aqueducts

- Senate Resolution for Damaging Conduits

VIII

Modern Equivalent:

State Statutes and Guidance, etc.

Summary

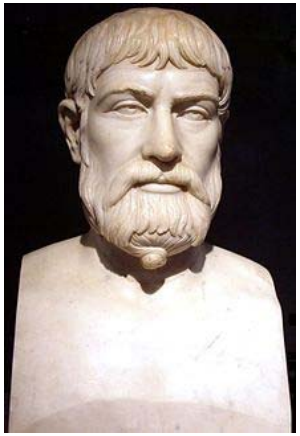
Comparison of Practices 97 AD to Now

Ancient Roman Practice	Modern Practice
De Aquaeductu Urbis Romae (System Description)	Water System Plan
Initial System Mapping	GIS
Facilities Inventory and Supply Yield Determinations	Hydraulic System Modeling
Water Balance to Control Theft/Fraud	Water Balance and Unaccounted Water Control
Bronze Calix-Orifice Control	Water Meters
Standard Pipe Dimensions	AWWA and ASTM Standards
Reliability and Redundancy Practices	Vulnerability and Sustainability Studies
Water Quality and Treatment Techniques	EPA and Safe Drinking Water Act
Water Quality Testing	Standard Methods
Preventative and Prioritized Maintenance	CMOM and PM Programs
Water Rights and Grants	Water Rights and Grants
Senate Resolutions for Legal Authority	State Statues and Guidance

In the End—Nearly 2,000 Years Later

- Not much has really changed
- Same intellectual foundation for organization and administration
- Ancients Developed Basic Framework of Modern Water System Planning

AQVA OMNIVM REBVS
OPTIMVS EST



"Water is the best of all things"

— **Pindar**

Greek Poet (c. 522 – c. 443 BC)

Next Time at a Restaurant

Order a “Hail Caesar” salad

with anchovies!

Brown AND Caldwell