THE MARCH 11TH SESSION

- Energy in water utilities (20 min)
- Introduction to pumping and pump design (45 min)
- Pump modeling exercise (30 min)
- Break (10 min)
- Introduction to optimization (25 min)
- Optimization in water sector (25 min)
- Modeling exercise – energy, leakage, pumping (30 min)

INTRODUCTION TO PUMPING AND PUMP DESIGN

Aalto University – 2019-03-11

EUR ING PhD MARKUS SUNELA

LEARNING OUTCOMES

- Name pump parts and describe centrifugal pump working principle
- Explain characteristic curve and list three most important curves
- Describe how pump speed control works and affinity laws related to it
- Calculate pump energy use
- Calculate/estimate pump flow (demand estimate) and head

QUESTION TIME (5 MIN)

- Discuss in small groups of 2–4
- List use cases for pumping in water supply and sewerage
- Explain the working principle of centrifugal pump
- Explain terms
  - Pump characteristic curves
  - System curve
  - Pump head: geodetic, static and dynamic head
  - Affinity laws

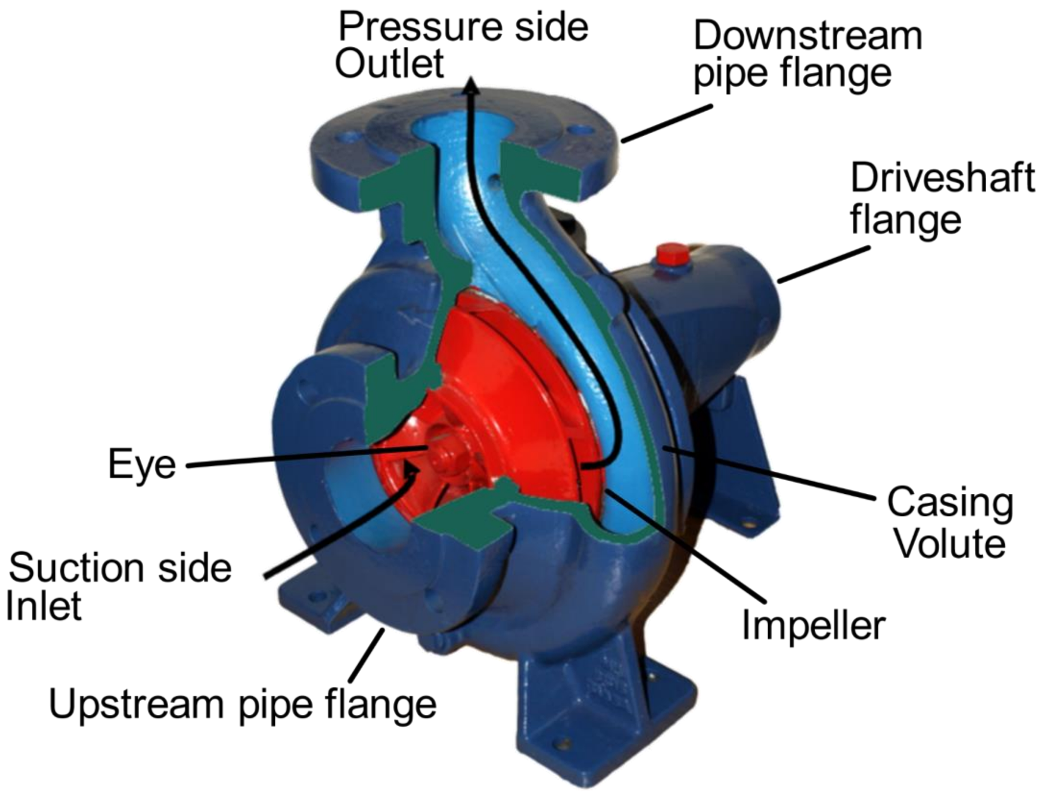
PUMP

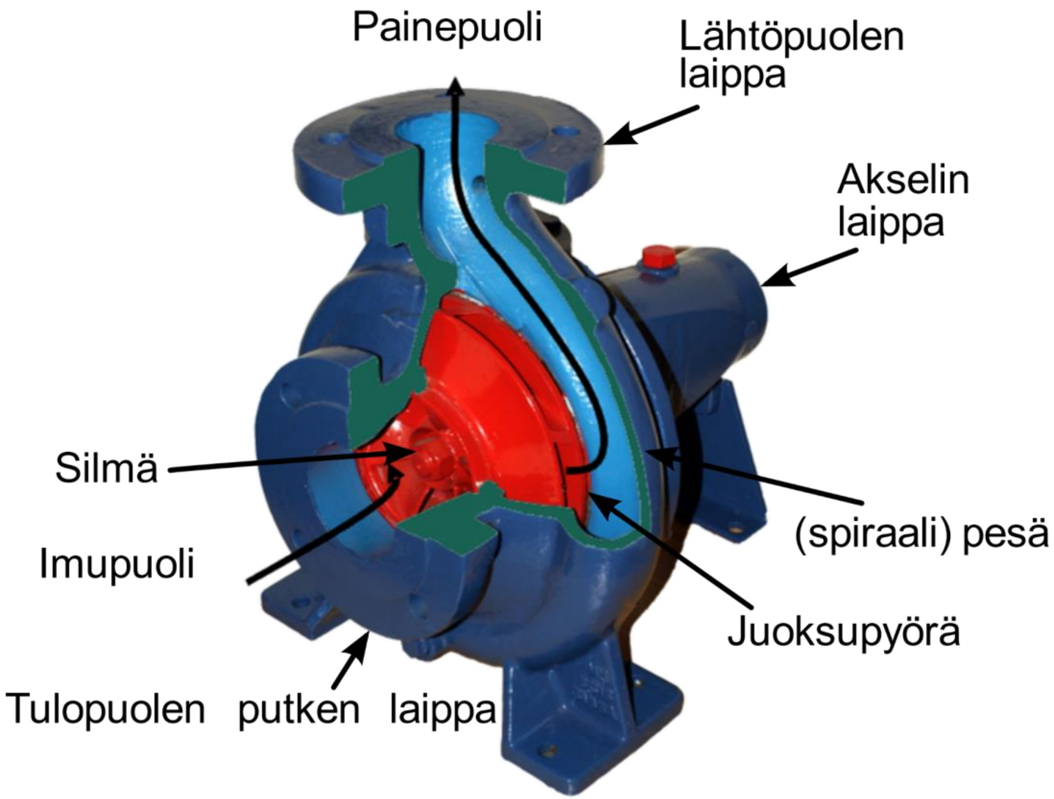
- Pump is a device that adds energy to liquid in order to move it or raise its pressure
  - Lifting water from lower to higher elevation
  - Transfer in pipe system – overcoming the head losses
  - Rising pressure – typically for process technical reasons

- Pump converts energy into hydraulic energy – velocity & pressure

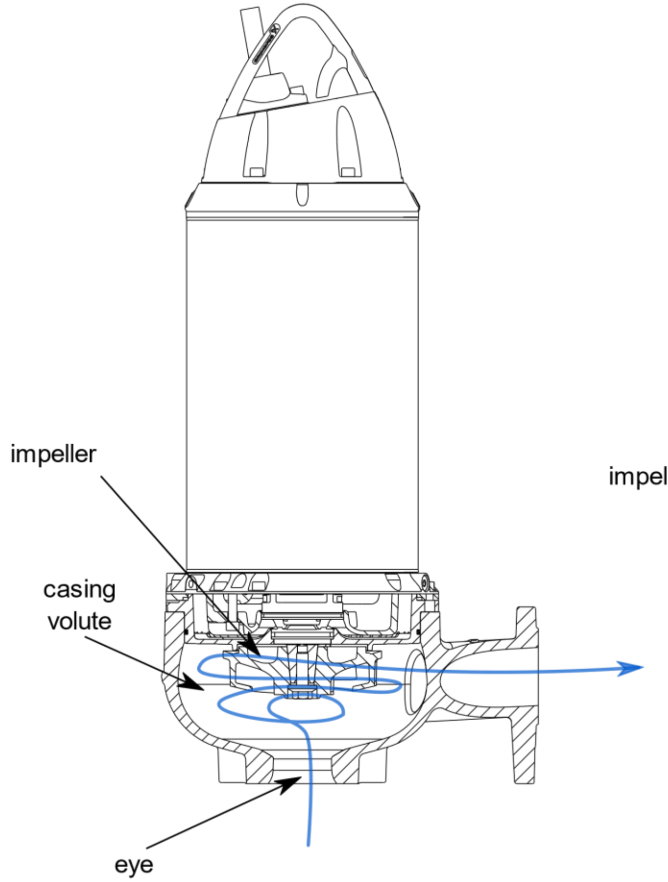
- There are a lot of different types of pumps
  - Main division between positive displacement and dynamic pumps
  - Most common type of pump is centrifugal pump (dynamic pump) that gives liquid more kinetic energy and then transforms that kinetic energy into potential energy (pressure)

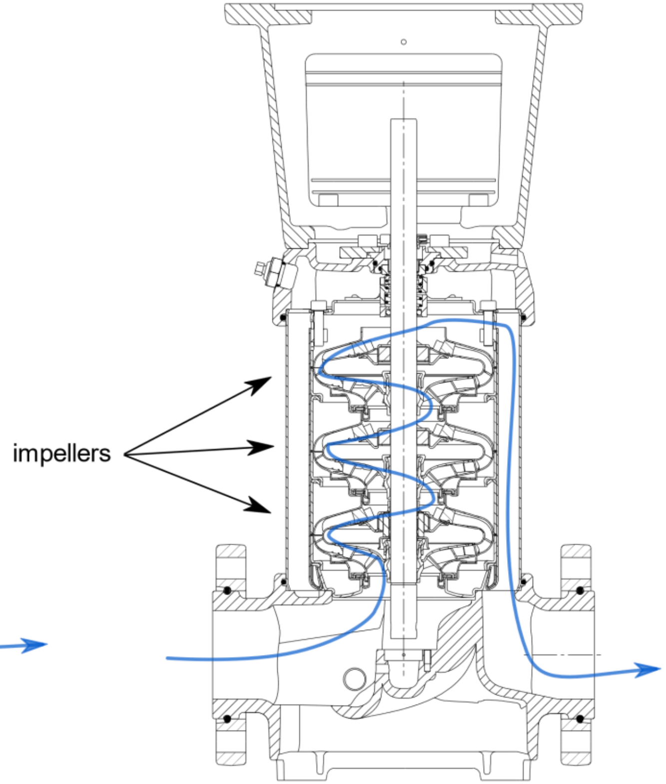
CENTRIFUGAL PUMP PARTS



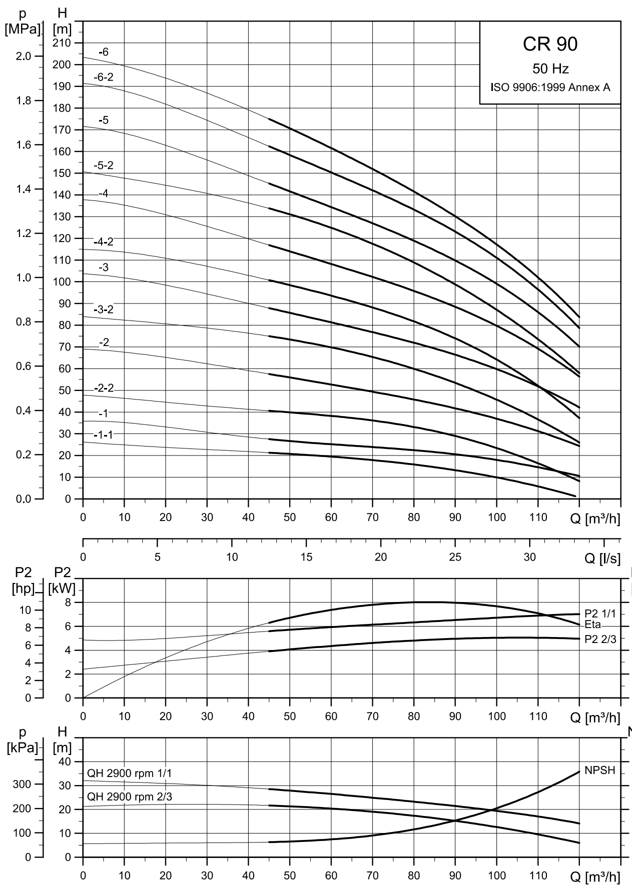


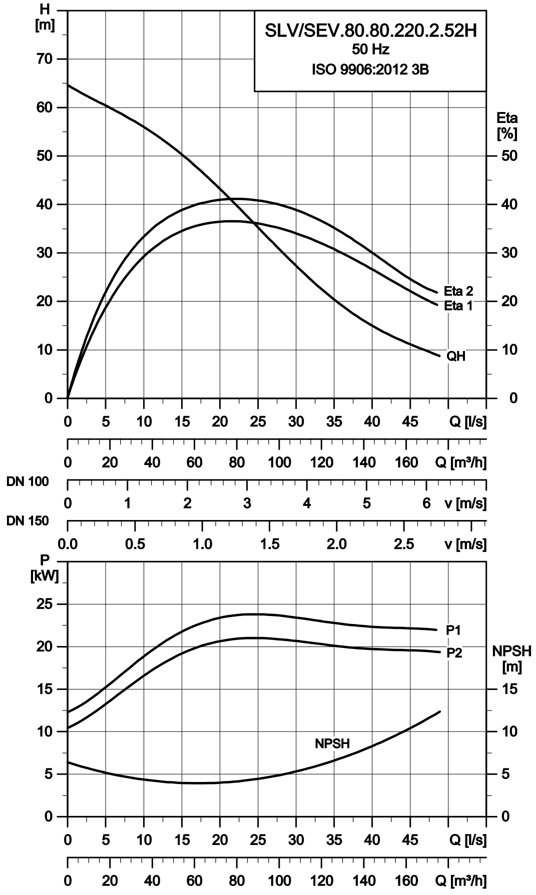
CENTRIFUGAL PUMP WORKING PRINCIPLE





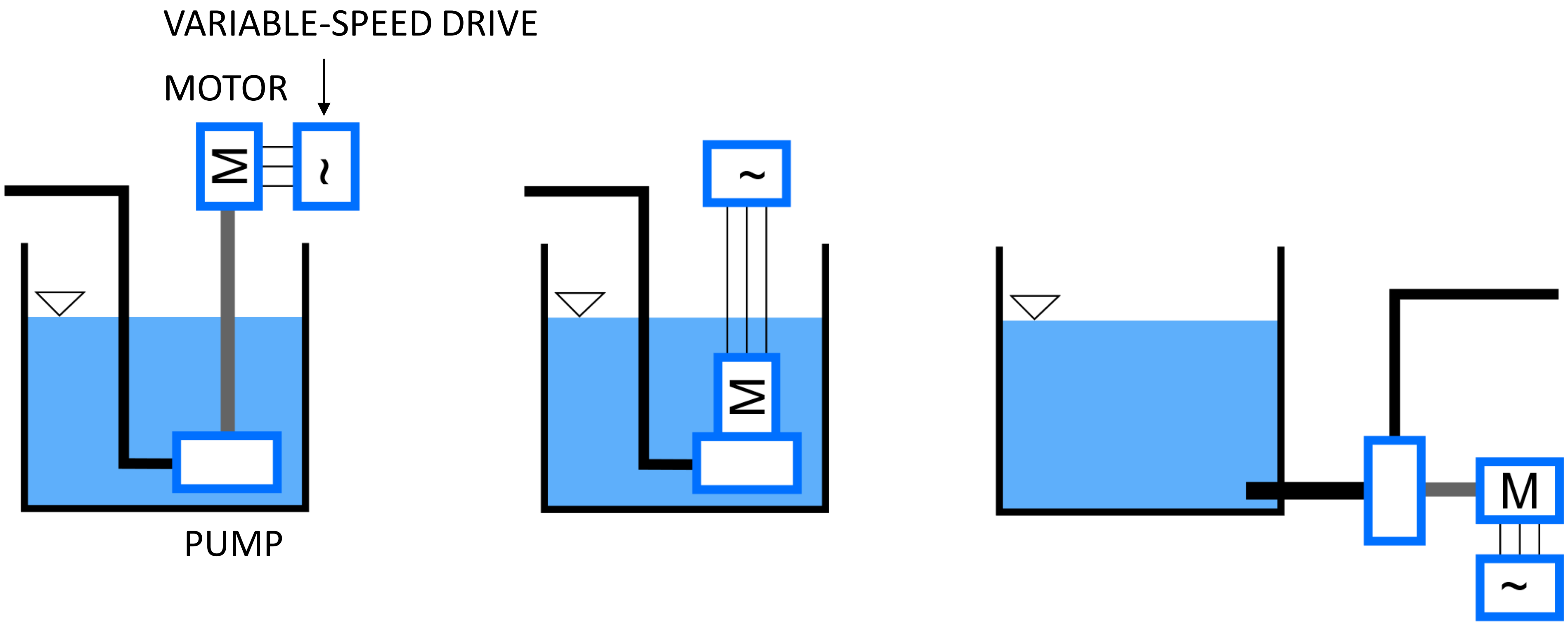
PUMP CHARACTERISTIC CURVES





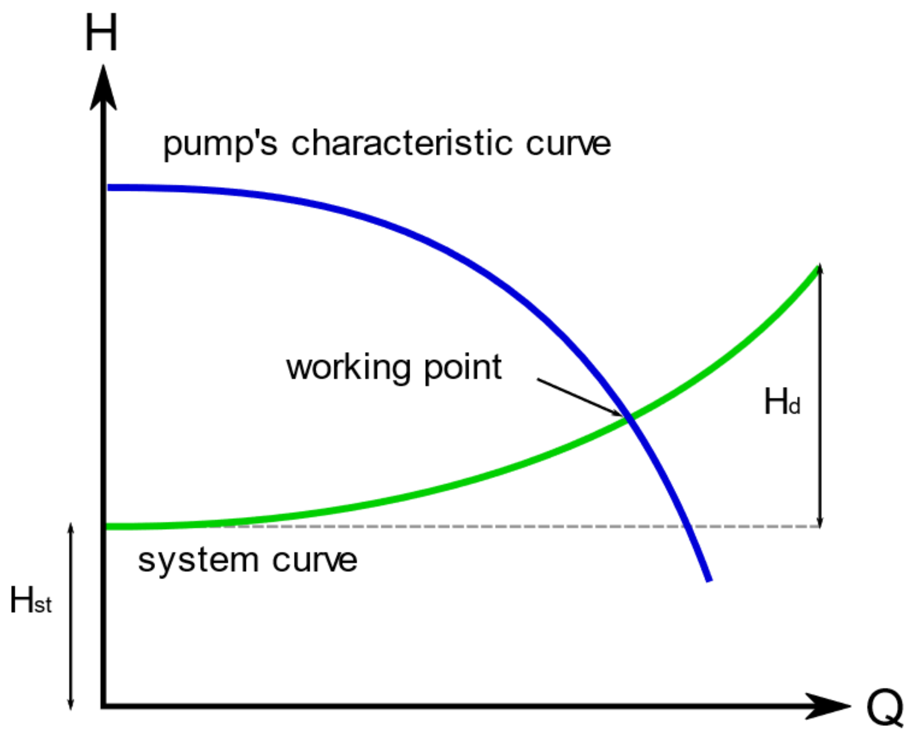
- Pump's properties are expressed as *characteristic curves* as a function of flow formed by testing pump with different flows and heads in a lab
- Most important is the QH curve
  - Pump's head as function of flow
- Other characteristic curves
  - Efficiency [%] – usually only pump losses
  - Power [kW] – P_1 & P_2 motor input power and pump shaft power
  - $NPSH_R$ [m] – required net positive suction head [m], important for cavitation

PUMP INSTALLATION OPTIONS



WET WELL SUBMERGED DRY WELL

PUMP WORKING POINT



- Pump produces some flow *Q* and head (lift) *H* – the *QH* point is called *working point*
- The point, where pump's *characteristic curve* (QH curve) intersects with the *system curve* representing the head losses in the system as a function of flow, becomes the working point
- H_{st} is *static head*: head required at zero flow, i.e. head/elevation difference between source and receiving ends
- $H_d(Q)$ is *dynamic head* (head loss) depending on the flow through pump:

$$\mathrm{H}_d(\mathrm{Q}) = h_f(Q) = f\,\frac{L}{D}\frac{v^2}{2g} = f\,\frac{8 \cdot L \cdot Q^2}{2g \cdot \pi^2 \cdot D^5}$$

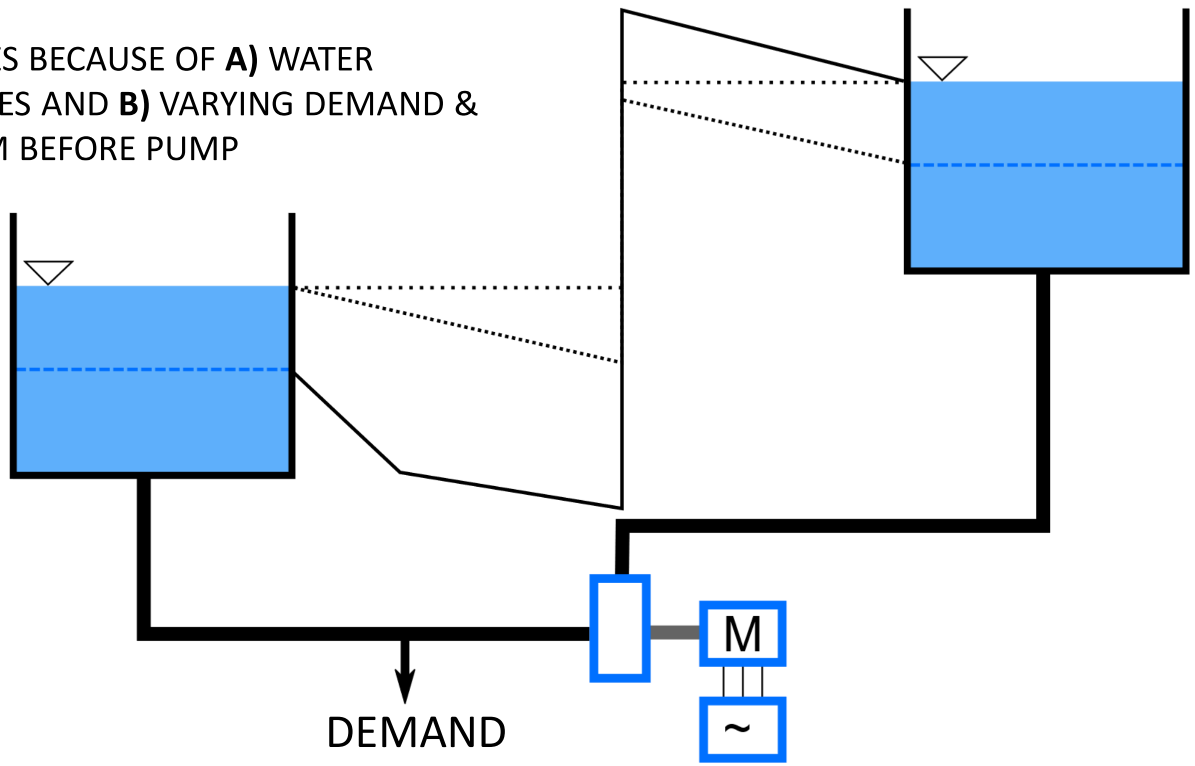
- Pump must produce total head $H=H_{st}+H_d(Q)$

PUMPING SYSTEMS AND PUMP CONTROL

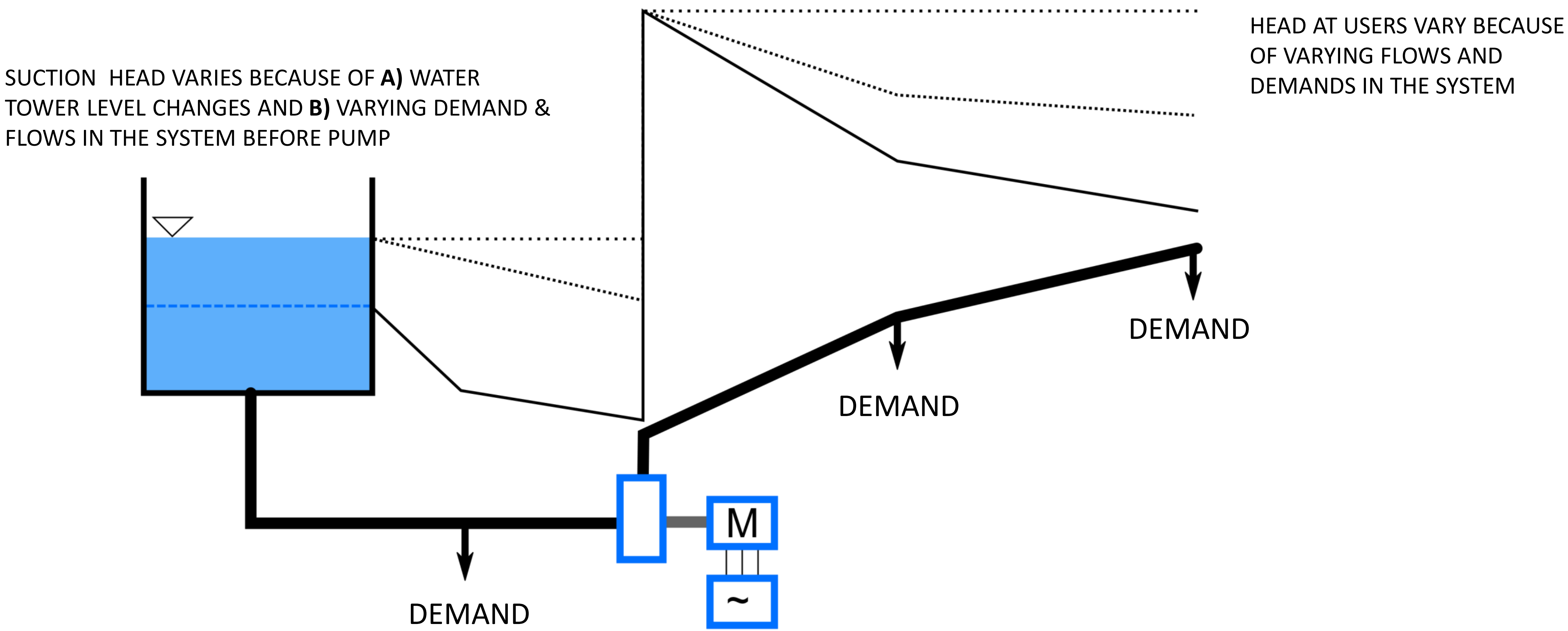
PUMPING SYSTEM – CONSTANT FLOW FROM TANK TO TANK

OUTLET HEAD VARIES BECAUSE OF **A)** WATER TOWER LEVEL CHANGES, CHANGES IN PUMP ROTATIONAL SPEED AND **B)** VARYING DEMAND & FLOWS IN THE SYSTEM AFTER PUMP

SUCTION HEAD VARIES BECAUSE OF **A)** WATER TOWER LEVEL CHANGES AND **B)** VARYING DEMAND & FLOWS IN THE SYSTEM BEFORE PUMP



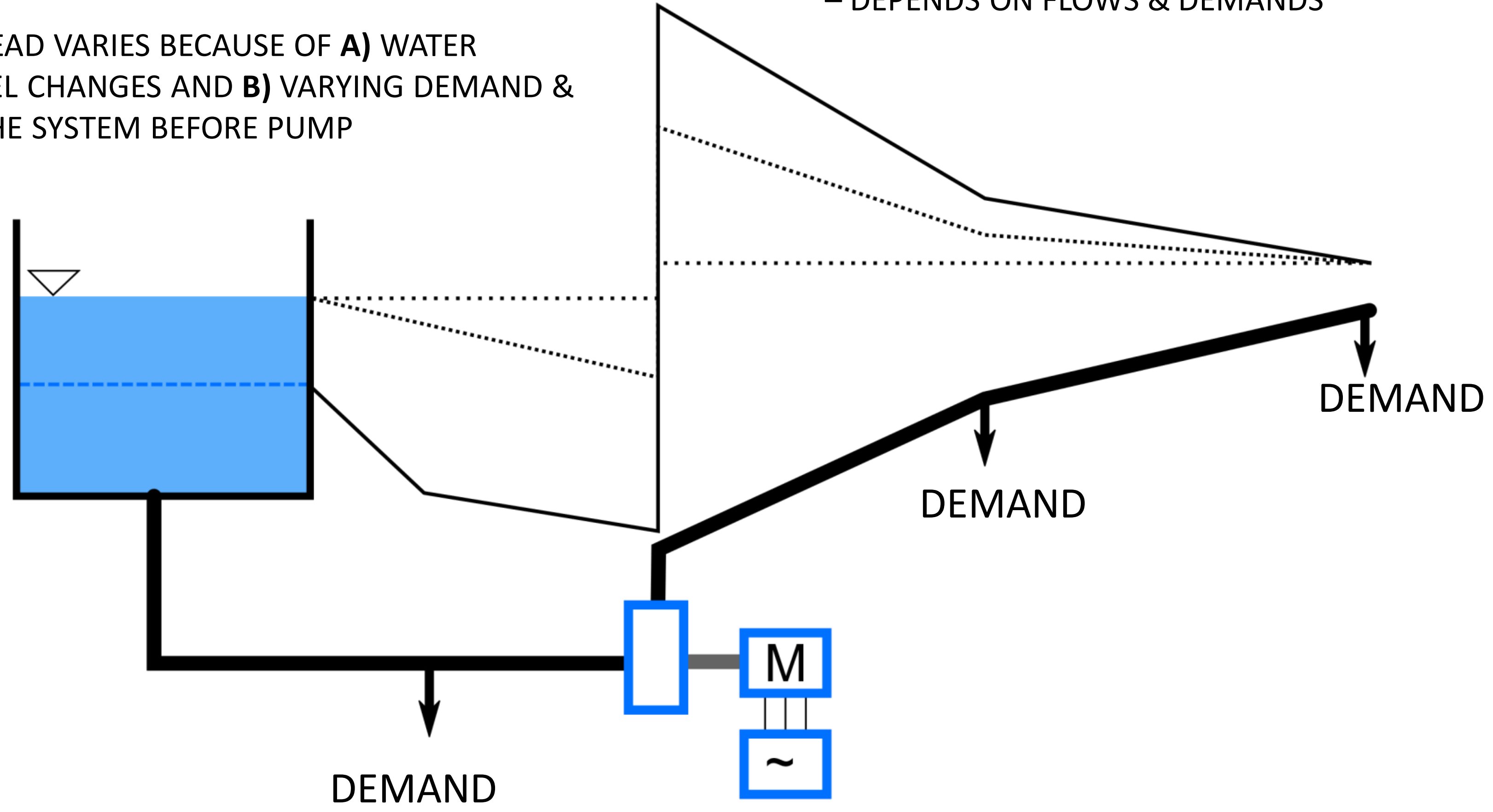
PUMPING SYSTEM – CONSTANT OUTLET PRESSURE



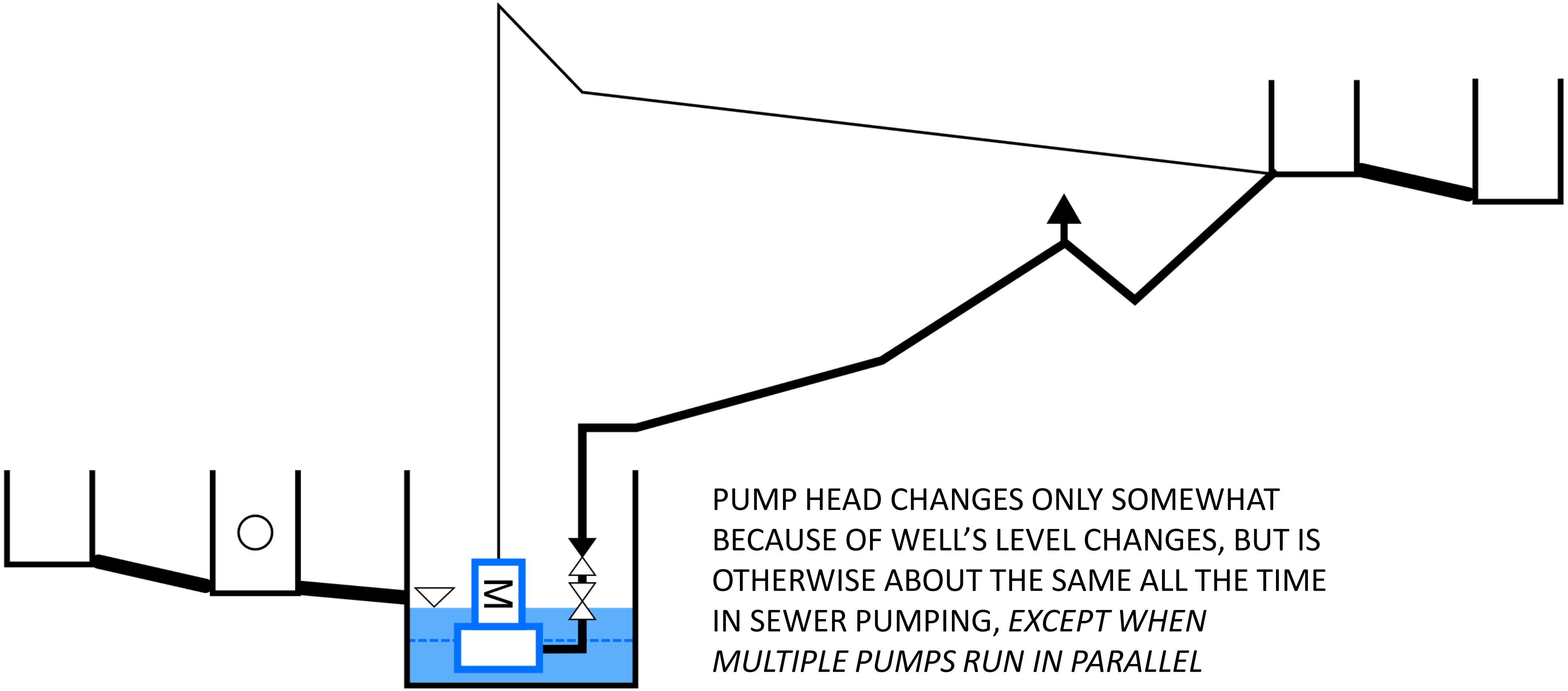
PUMPING SYSTEM – CONSTANT USER PRESSURE

OUTLET HEAD CHANGES TO KEEP THE PRESSURE AT DESIRED VALUE AT THE END OF THE NETWORK – DEPENDS ON FLOWS & DEMANDS

SUCTION HEAD VARIES BECAUSE OF **A)** WATER TOWER LEVEL CHANGES AND **B)** VARYING DEMAND & FLOWS IN THE SYSTEM BEFORE PUMP



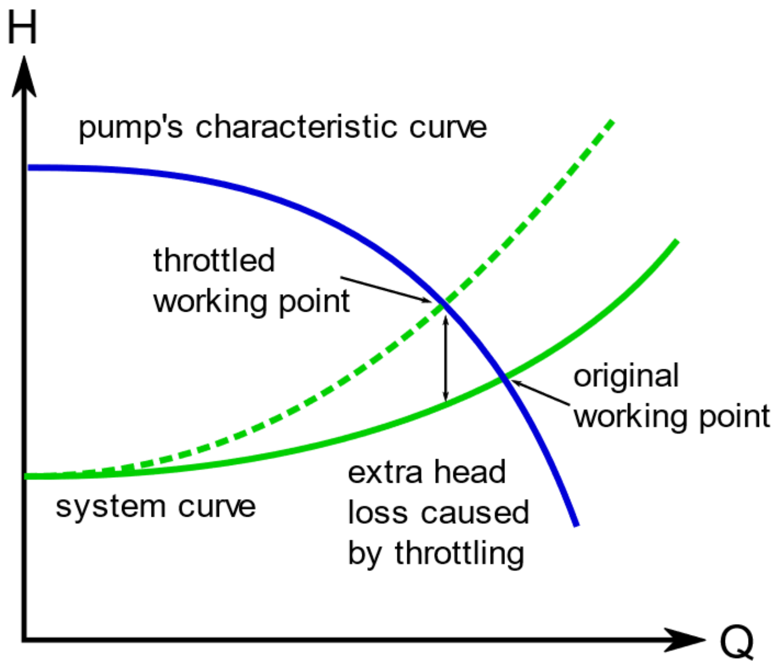
PUMPING SYSTEM – SEWAGE PUMPING



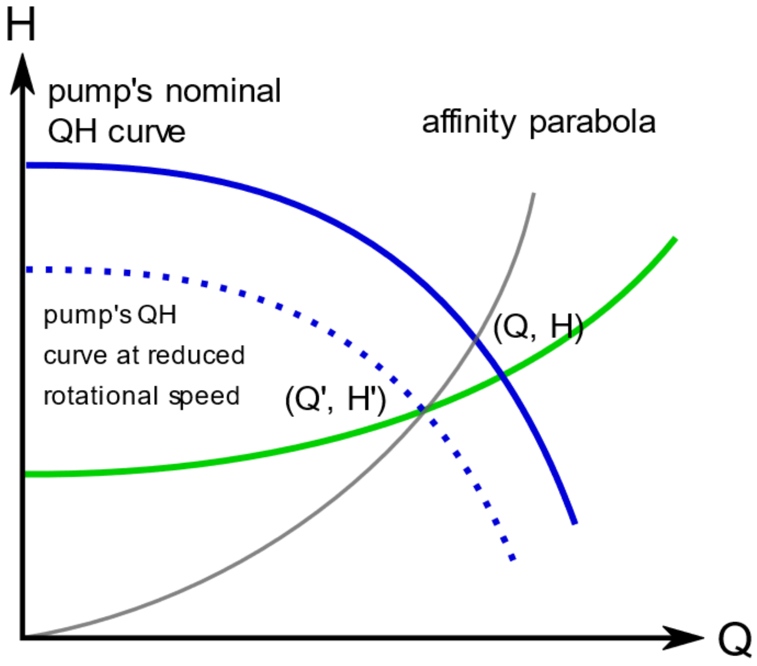
PUMP HEAD CHANGES ONLY SOMEWHAT BECAUSE OF WELL'S LEVEL CHANGES, BUT IS OTHERWISE ABOUT THE SAME ALL THE TIME IN SEWER PUMPING, *EXCEPT WHEN MULTIPLE PUMPS RUN IN PARALLEL*

CONTROLLING FLOW AND PRESSURE

THROTTLING – USING VALVE TO CAUSE EXTRA HEADLOSS IN THE SYSTEM



VARIABLE SPEED PUMPING – PUMP’S ROTATIONAL SPEED IS CHANGED TO MATCH THE DESIRED WORKING POINT



THIRD WAY IS BY-PASS CONTROL: PART OF THE GENERATED FLOW IS RETURNED TO THE SUCTION SIDE OF THE PUMP – MORE FLOW IS GENERATED AND THUS THE HEAD IS LOWERED

FOURTH WAY IS USING MULTIPLE PUMPS

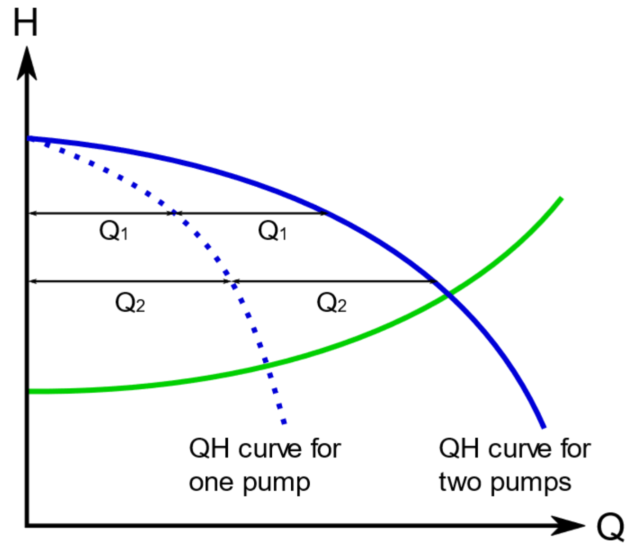
AFFINITY LAWS

- Pump’s QH curve can be modified by chaning
  - Pump’s rotational speed
  - Impeller diameter

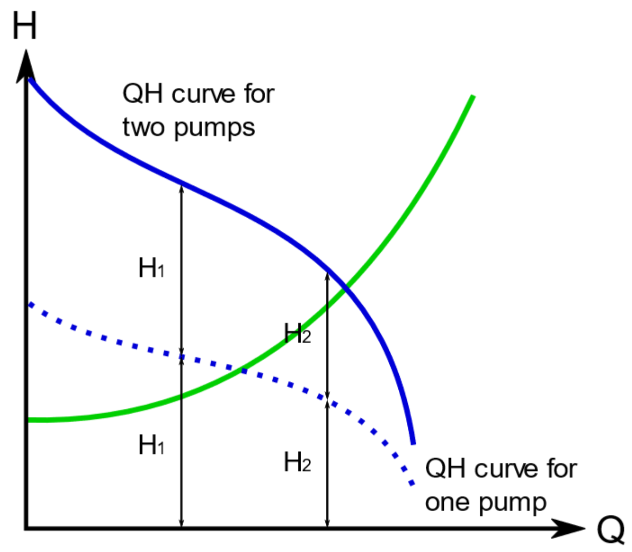
- Lowering rotational speed or using smaller impeller lower the QH curve and move it left towards H-axis

- Affinity laws describe the change
  - $\frac{Q'}{Q} = \frac{n'}{n} = \frac{D'}{D}$
  - $\frac{H'}{H} = \left(\frac{n'}{n}\right)^2 = \left(\frac{D'}{D}\right)^2$
  - $\frac{P'}{P} = \left(\frac{n'}{n}\right)^3 = \left(\frac{D'}{D}\right)^3$
- Rotational speed is directly proportional to the frequency

MULTIPLE PUMPS WORKING IN PARALLEL OR SERIES



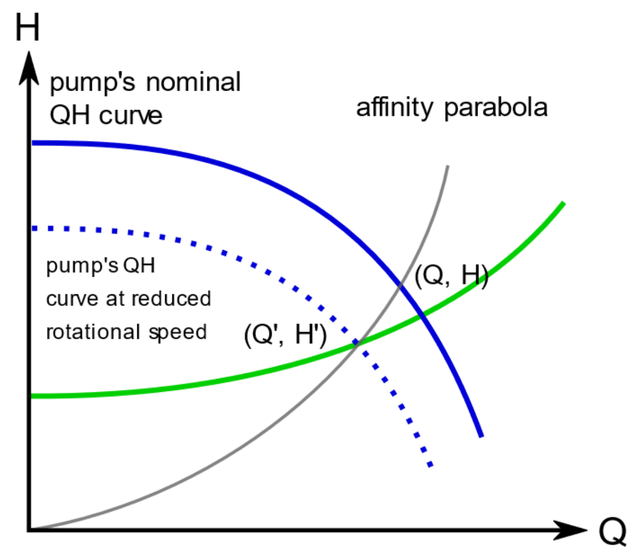
PUMPS WORKING IN PARALLEL
Pump curves summed in Q-direction
Flow doesn’t double (more losses as flow gets bigger)



PUMPS WORKING IN SERIES
Pump curves summed in H-direction
Head doesn’t double (more losses as flow gets bigger)

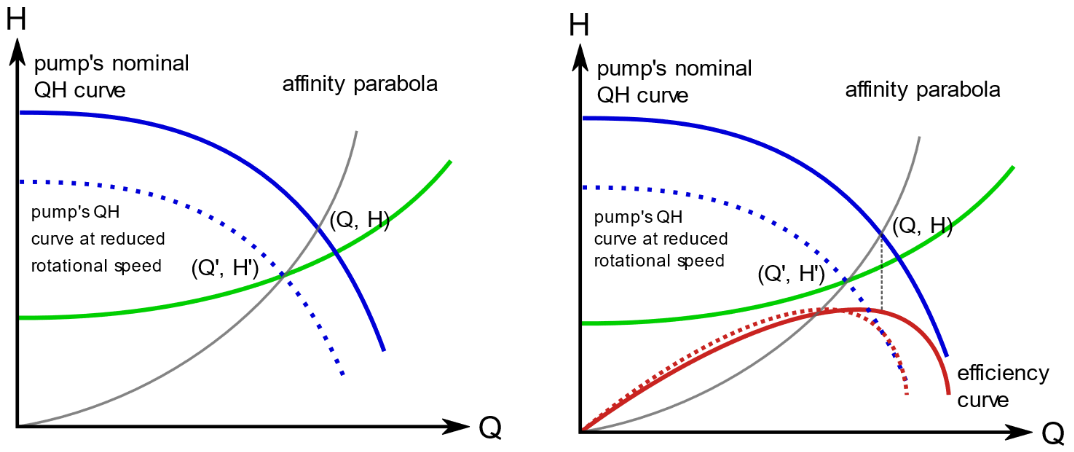
AFFINITY PARABOLA

- Affinity parabola is formed by fitting function $H(Q) = a \cdot Q^2$ through desired working point (Q', H')
- Reference working point on nominal QH curve, (Q, H), can then be solved as intersection of the nominal curve and affinity parabola
- (Q, H) is used for calculating relative speed using affinity laws



$$\frac{n'}{n} = \frac{Q'}{Q} \quad \text{or} \quad \frac{n'}{n} = \sqrt{\frac{H'}{H}}$$

AFFINITY PARABOLA & EFFICIENCY



- Pump's hydraulic efficiency is approximately the nominal efficiency at working point (Q, H)
- In reality the efficiency is slightly lower when rotational speed is reduced – the effect is called frequency scaling

EFFECT OF LOWERING ROTATIONAL SPEED ON EFFICIENCY

Table 1 | Different efficiency components at various loads and rotational speeds

		Efficiency			
Hz	**Load (%)**	**Motor (%)**	**VSD (%)**	**Pump (%)**	**Total (%)**
50.0	100.0	85.0	97.9	80.0	66.6
45.4	75.0	85.5	97.9	79.8	66.8
39.7	50.0	84.5	97.3	79.5	65.4
31.5	25.0	77.9	96.5	79.1	59.4
25.0	12.5	65.6	95.7	78.6	49.3
18.4	5.0	43.8	95.0	77.9	32.4
14.6	2.5	28.1	94.7	77.4	20.6
10.8	1.0	13.5	94.3	76.7	9.8

Sunela & Puust, 2015, A visual tool to calculate optimal control strategy for non-identical pumps working in parallel, taking motor and VSD efficiencies into account, Water Science & Technology (15.5), pp. 1115-1122

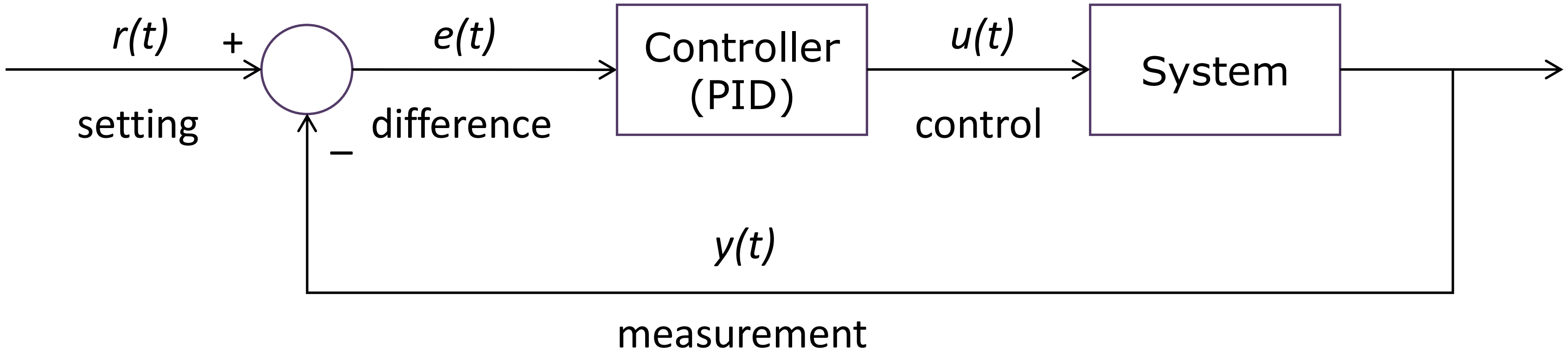
PUMP ENERGY USE

- Pumping power (produced hydraulic power) is $P = \rho \cdot g \cdot Q \cdot H$
  - Shaft power $P = \frac{\rho \cdot g \cdot Q \cdot H}{\eta_P}$
  - Electrical power $P = \frac{\rho \cdot g \cdot Q \cdot H}{\eta_P \cdot \eta_M \cdot \eta_{VSD}}$
- Even tough using variable speed pumping (lowering rotational speed) reduces efficiencies, it still saves a lot of energy, because of much lower Q and H, which dominate the power equation

- Always compare calculated energy use for longer period of time, for example kWh/d, kWh/a or kWh/m³, when comparing efficiency of different solutions

- Energy calculations must be done using average or ”normal” situation
  - Don’t optimize for maximum (<10 % of time) – optimize for typical (>80 % of time)

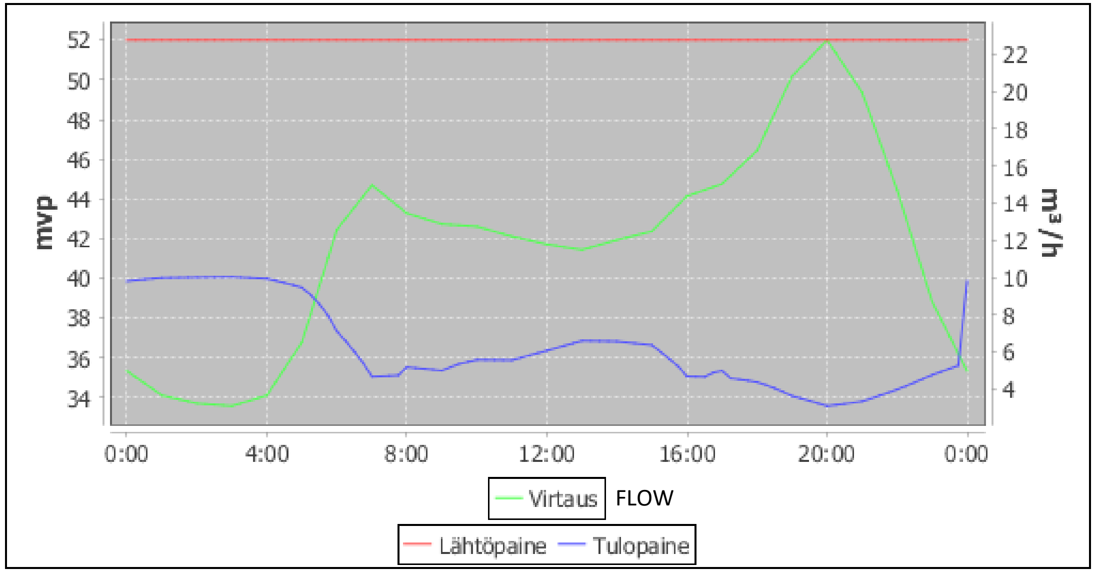
PUMP CONTROL



- In pumping *r(t)* and *y(t)* are the target setting and measured value for the parameter – typically flow [m³/h] or pressure [bar], sometimes tank level or some other parameter
- Controller's output, control *u(t)*, is frequency setting for variable speed drive (about 20–55 Hz)
- Pump rotates relative to frequency and produces certain flow and pressure as a part of the system. Sensors measure the flow and pressure.

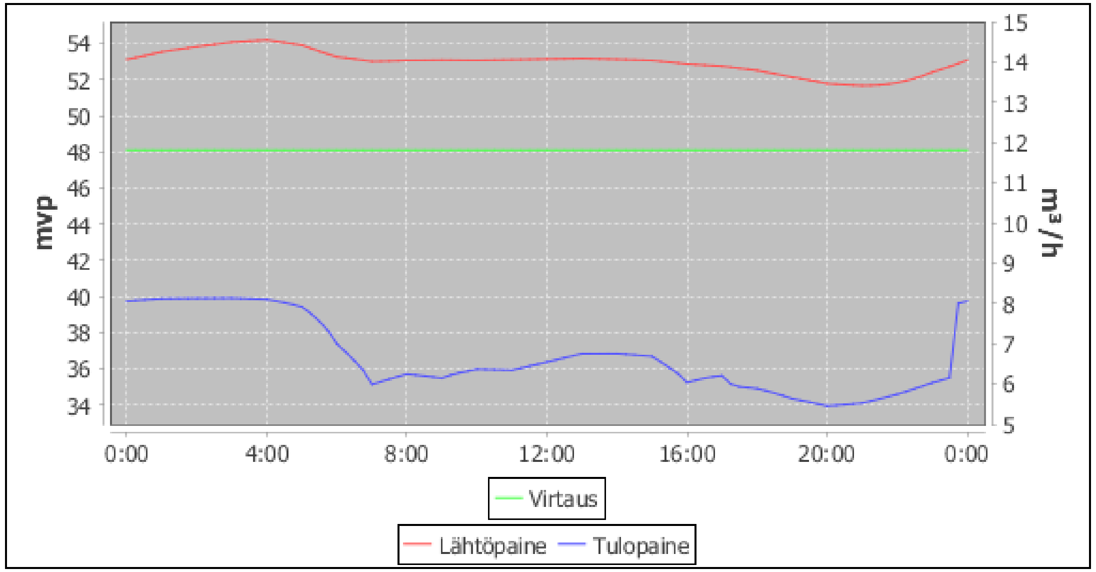
EFFECT OF CONTROL STRATEGY ON FLOW AND HEAD

CONSTANT OUTLET PRESSURE CONTROL



INLET PRESSURE OUTLET PRESSURE

CONSTANT FLOW CONTROL



PUMP DESIGN

DIFFERENT PUMPING STATION TYPES

- Sewer and storm water pumping stations
  - Lift water from the lowest points in the network
  - Along long transfer lines
  - Stable working point: constant flow, constant head
  - Low efficiencies, operation must be robust

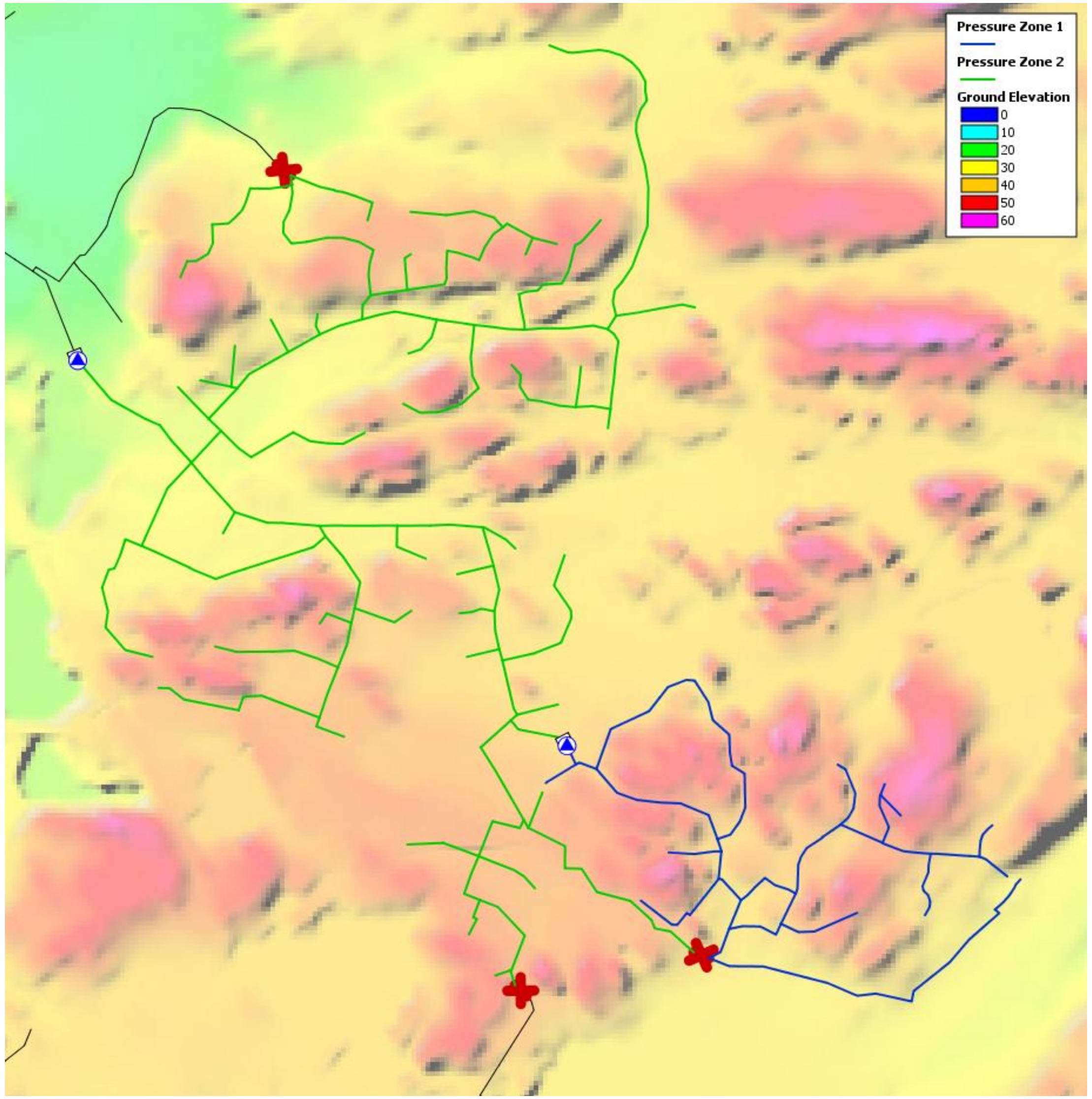
- Raw water and network pumps at water sources
  - Flow range is typically small
  - Typically quite little variation in head (inlet head is more or less fixed)
  - Important to have good reliability and efficiency

- Pressure booster pumps in water distribution network
  - Typically high flow variability (minima < 0.1 x maxima)
  - Both inlet and outlet pressures can vary with wide range
  - Fire flows, pipe bursts, different control strategies and settings…

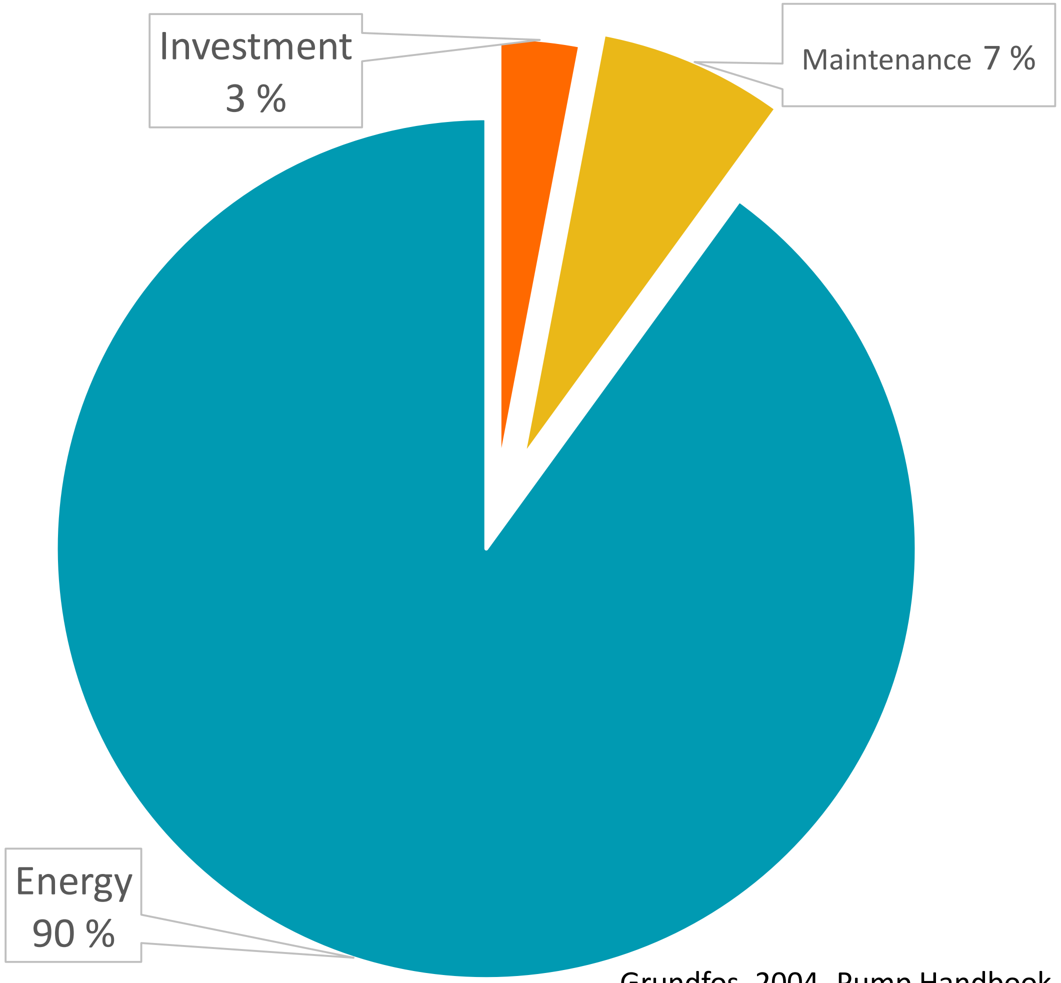
PRESSURE ZONES

- Network should be designed so that the elevation differences in one pressure zone are less than 30-40 meters
  - Otherwise pressure will be too high in the lowest parts of the network or too low at the highest
  - With 40 m difference 30 m pressure at the highest location means 70 m pressure at the lowest

- Pressure zoning and pressure booster stations
  - Gate valves are closed so that water enters the higher area through one or two pipes, in which as pressure booster station is installed
  - Location is chosen so that the pipes have enough capacity and inlet pressure stays high enough, >2.0 bar, and outlet pressure low enough <8.0 bar
  - Ideally at least two booster stations for improved reliability
  - Booster stations provide monitoring points in the network



PUMP LIFE CYCLE COSTS

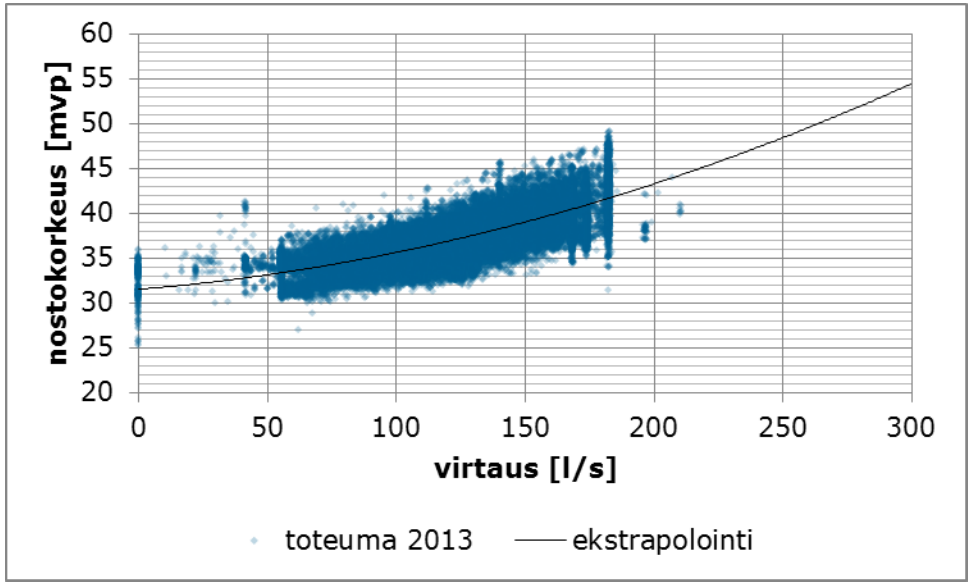


Grundfos, 2004, Pump Handbook

- Energy use is about 90 % of LCC
- Maintenance about 2-5 %
- Initial cost about 5-8 %
- It's usually better to invest more in pumps and motors with higher efficiency and more intelligent control (VSD)

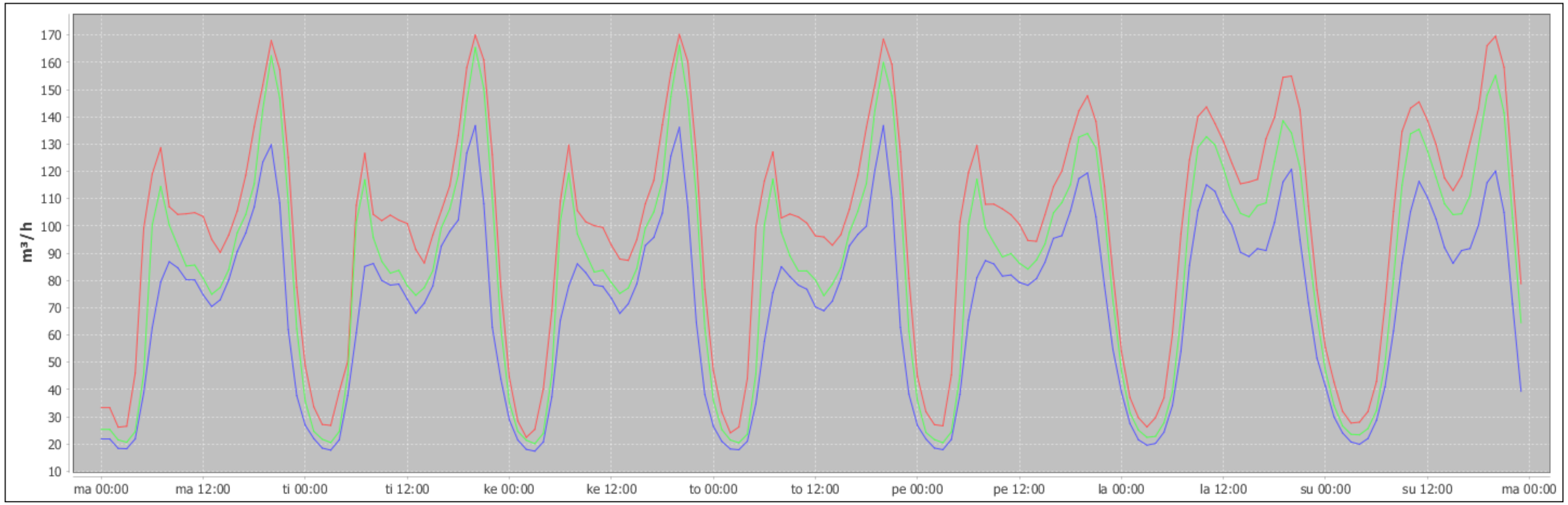
PUMP DESIGN

- In order to design a pump one must know the working regime (flow range and total head range)
  - Both extremes and average values important – must be able to cope with minima and maxima, optimize for typical
  - Minimum inlet pressure (typically > 1.0 bar) and maximum inlet pressure (<8.0-10.0 bar)
- Working regime depends on the behavior of the system and control strategy chosen for the planned pumping station
- Pipes, control strategy, settings etc. should be designed together if possible
- Highly recommended to use model – of the whole system for design
- Account for cavitation, if the inlet pressure is low of flow is really high

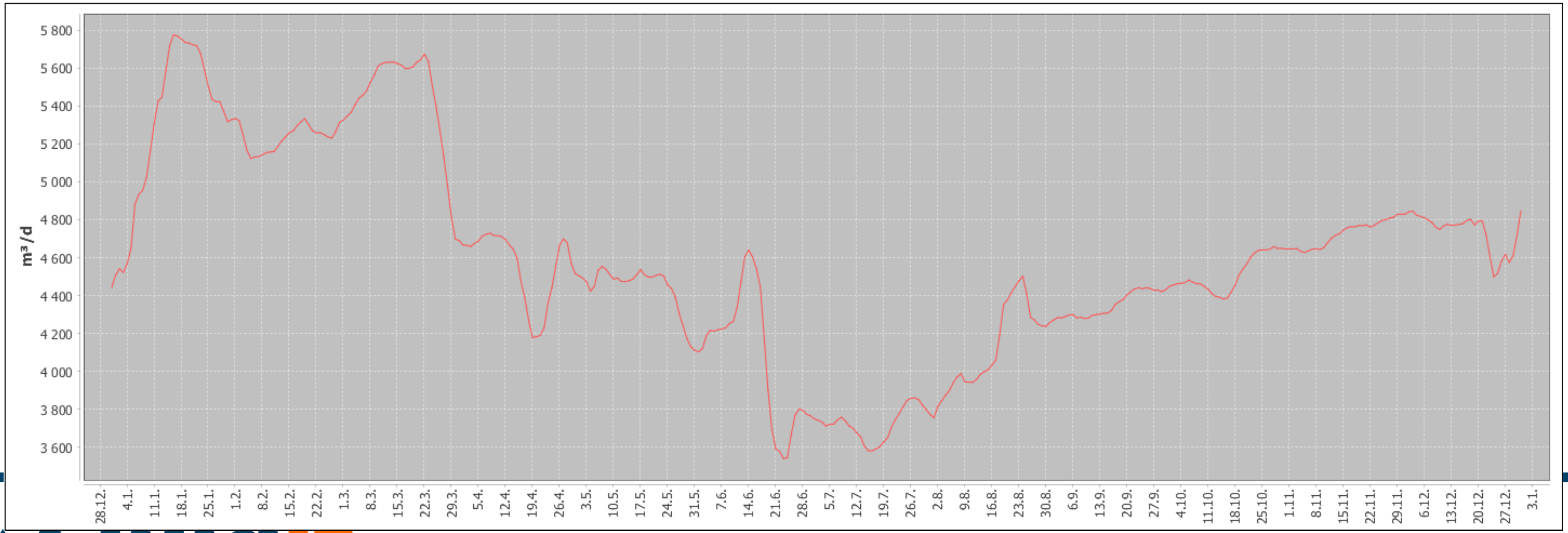


WATER USE – DAILY VARIABILITY

WATER USE – WEEKLY AND YEARLY

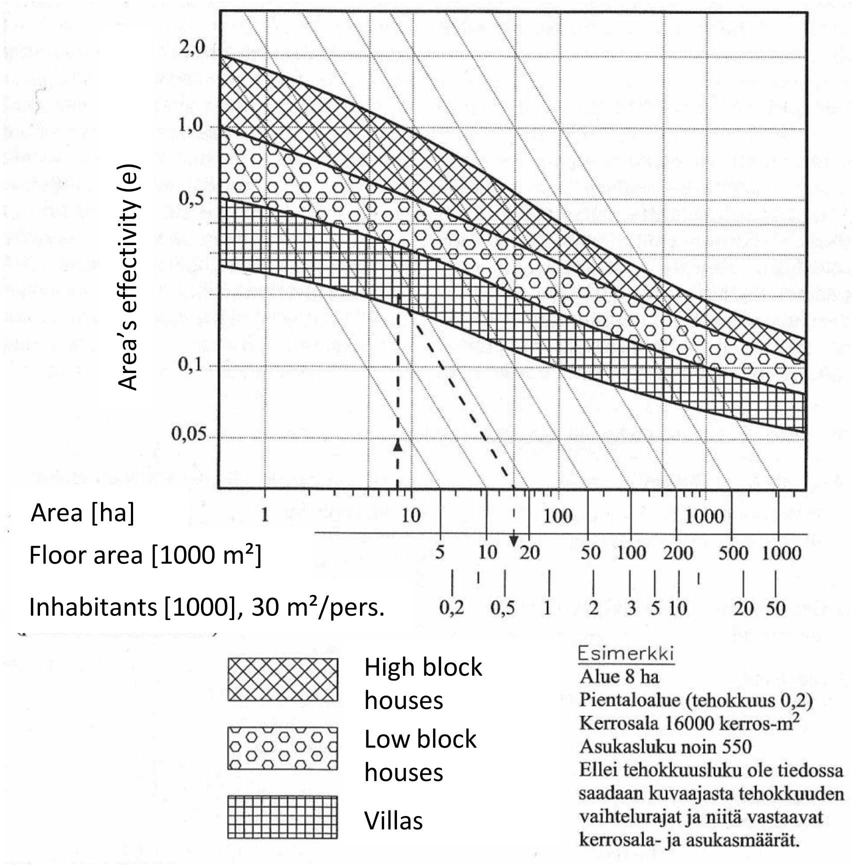


TYPICALLY MAXIMUM DAILY DEMAND IS 7–10 TIMES MINIMUM DEMAND AND 1.3–2.5 TIME AVERAGE DEMAND

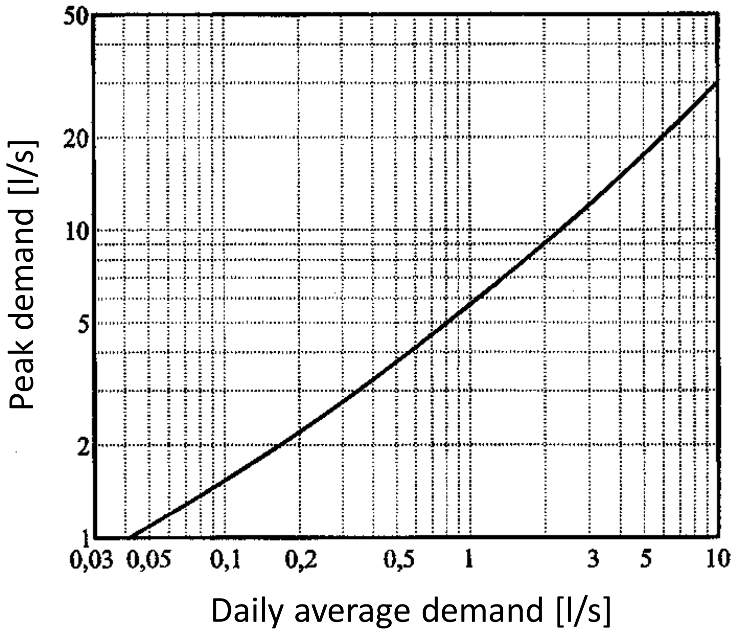


THE ABSOLUTE MAXIMUM DEMAND IS 1.2–1.8 TIMES THE MAXIMUM DAILY DEMAND

ESTIMATING WATER DEMAND



INCLUDES LEAKAGE
AND FIRE FLOWS



Reference: RIL 124-2, pages 237 and 272

ESTIMATING LEAKAGE

- In sewer network leakage is always significant
  - Especially melting of snow always causes significant peak flows
  - It's common that maximum daily flow is 2–5 larger than average
  - For new areas leak coefficient 1.1–1.3 or leakage 0.5–1.0 l/s·km can be used
  - For combined sewers the effect of runoff must be taken into account
- In water distribution a leak coefficient of, for example, 1.08 can be used
- Select in co-operation with the client

ESTIMATING DEMAND

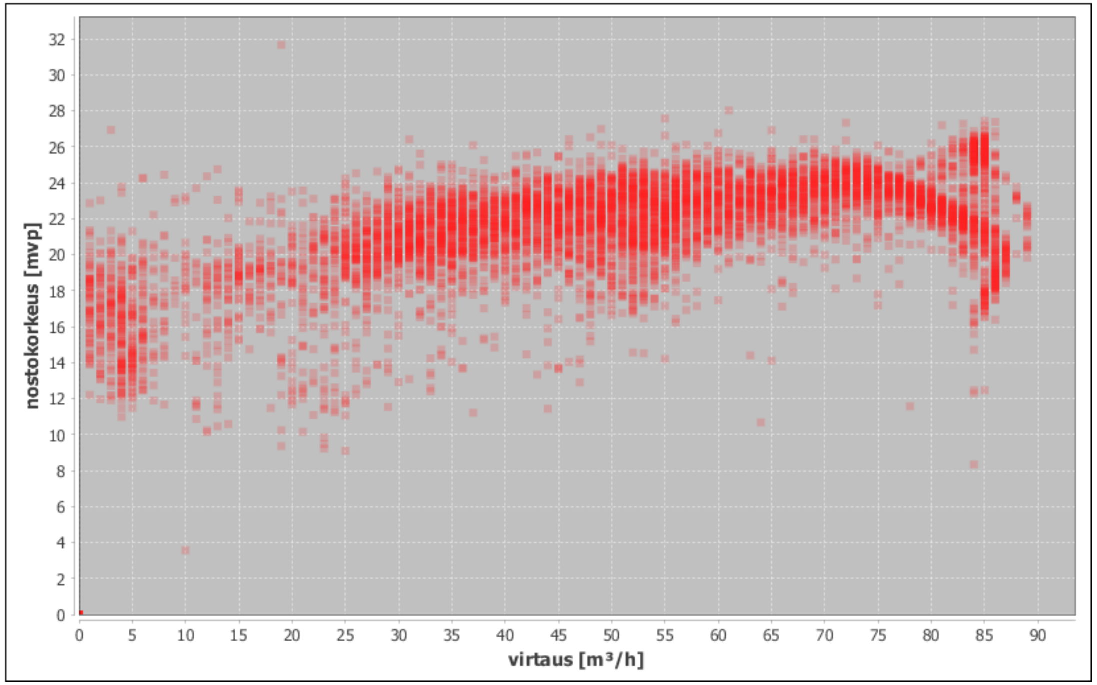
- Average demand is calculated using specific demand, for example 110-160 l/d pers. and 50 l/d job, or estimating inhabitants, 4 ppl/villa
- Design requires estimate of maximum daily demand and peak hour demand
- These maxima define the design – system must be able to work in the maxima – but energy costs are calculated using normal day
- Maximum daily demand
  - $Q_{d,max} = k_d \cdot Q_d$

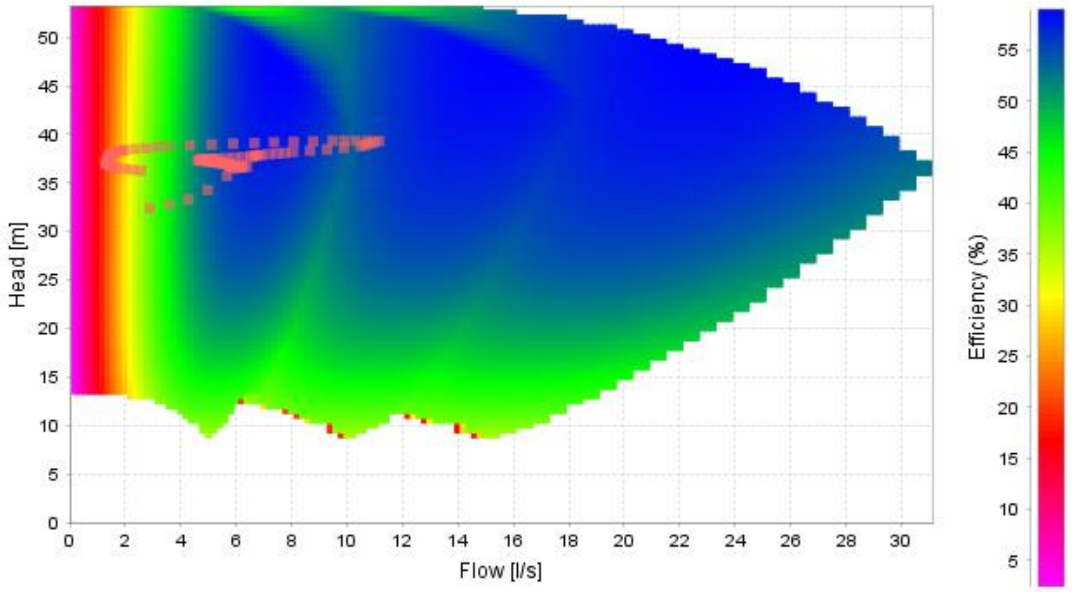
- Average hourly demand $Q_h = {}^{Q_d}/_{24}$
- Maximum hourly demand $Q_{h,max} = k_h \cdot Q_h$
- Peak hour demand $Q_{max} = Q_h \cdot k_d \cdot k_h$
- Minimum hour coefficient $k_{h,min} = 0{,}3$
- Demand values are modeled and head taken from the simulation results

Inhabitants	Daily coefficient	Hourly coeff.
<10 000	1,8…1,5	2,4…2,0
10-30 000	1,5…1,4	2,0…1,7
30-100 000	1,4…1,3	1,7…1,6
>100 000	1,3	1,6…1,5

RIL 124-2, page 243

PUMP WORKING REGIME

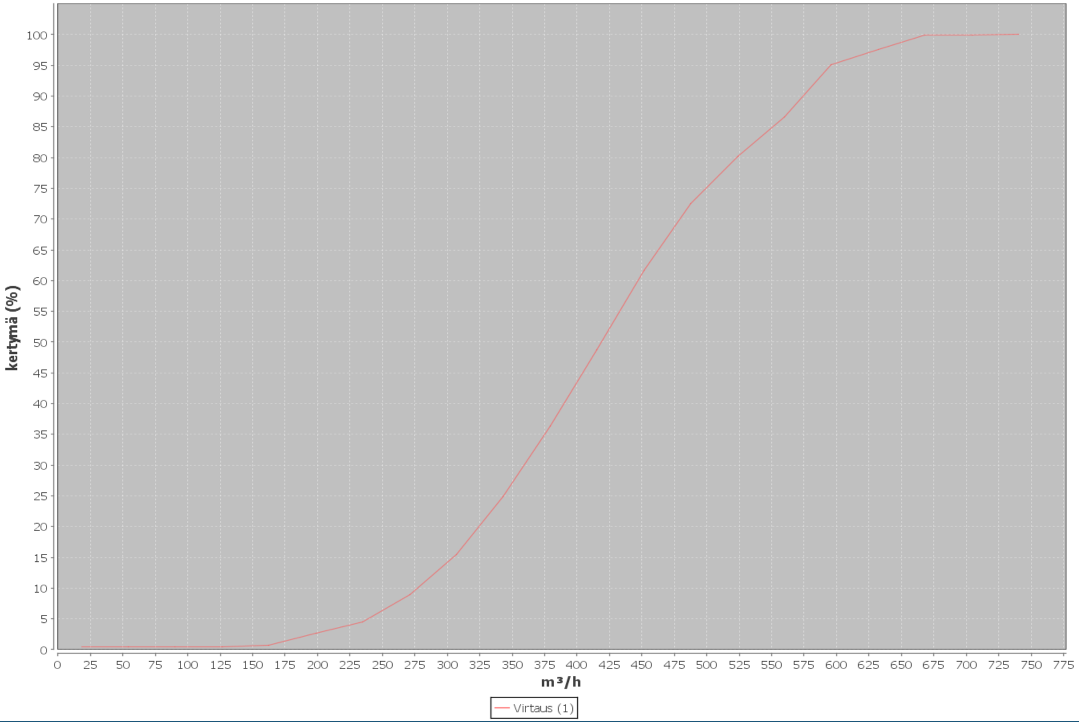


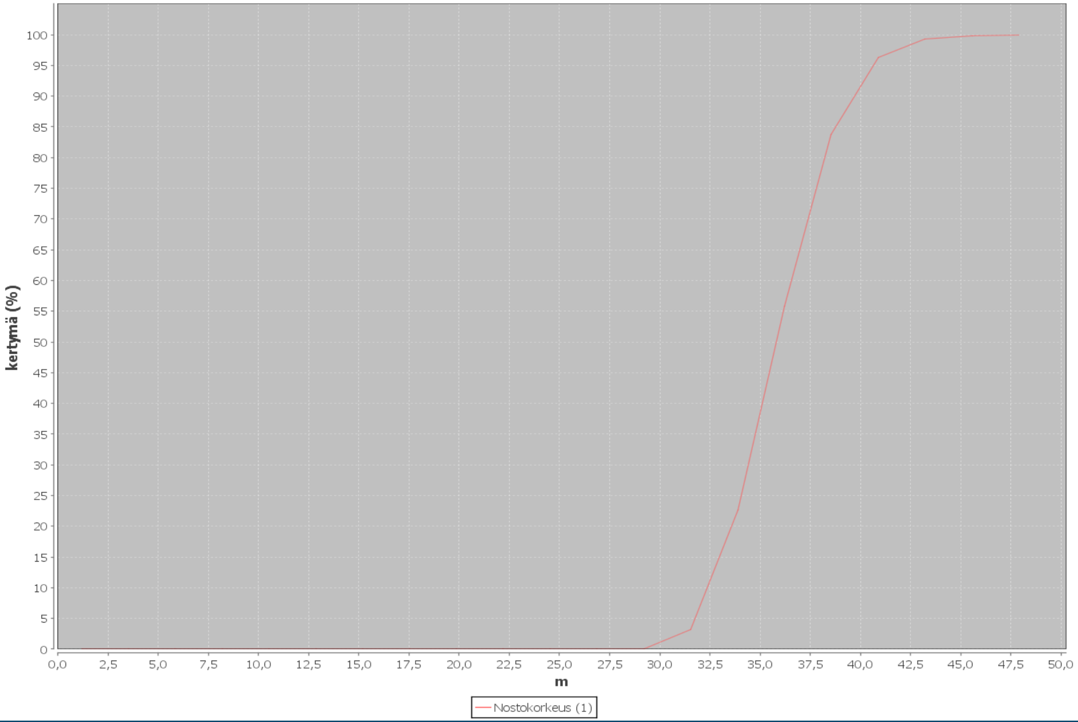


FLOW AND HEAD STABILITY

Stability is a useful indicator to analyze, how much of the time a value is with some range, what the minima and maxima are, and how important they are. Using the flow and head stability, it's easy to get a good picture of the working regime.

Here a year's worth of 1 min data is processed by sorting the values from smallest to largest and plotting the cumulative number of points processed.

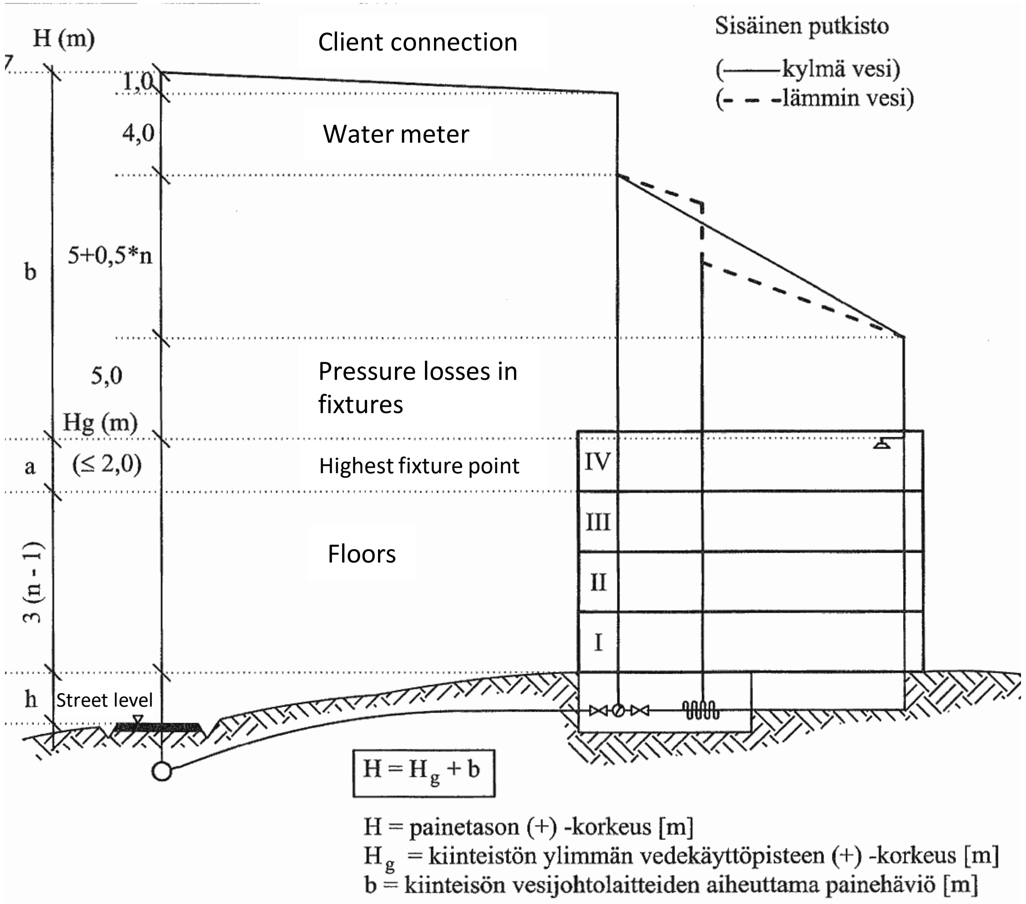




CALCULATING PUMP HEAD

- Pressure booster station and water source pumping head should always be modeled under different scenarios (average, maximum, minimum)
  - Suction pressure typically varies significantly
  - Ensuring discharge pressure requirement and design constraints
- Normal sewer pumping station is easier, because the discharge pressure is practically constant and suction head varies typically only about a meter
- When an existing pumping station is replaced, measurements can be used and extrapolated if needed

MINIMUM PRESSURE REQUIREMENTS

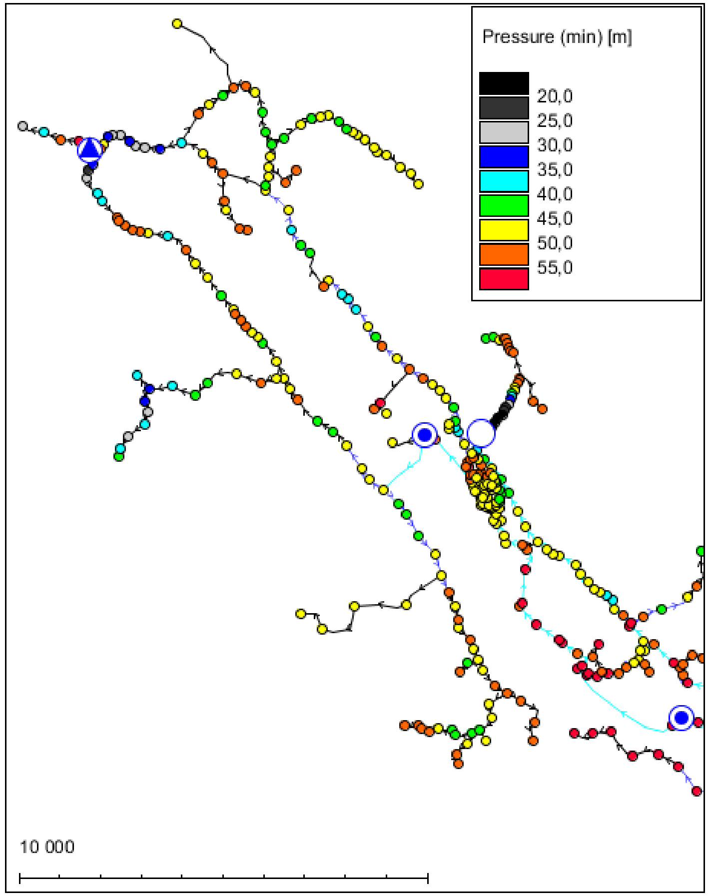


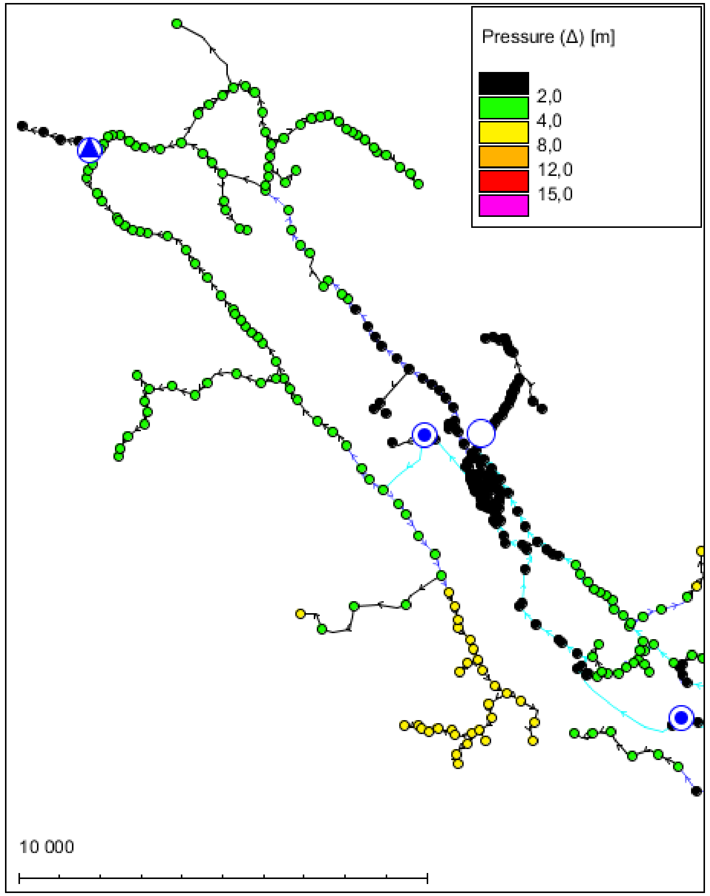
- Every user has to have sufficient pressure all the time
- 20–25 m in mains on street level, in some countries as low as 10–15 m
- More exact minimum pressure requirement depends on the number of floors *n*
  - $p = 3 \cdot (n - 1) + 22$ [m]

PUMP AND PIPE DESIGN

- Pipe, pump and the control method need to be designed at once – behavior of the whole system, account for both capital and operational costs
- There should always be at least two pumps working in parallel – the absolute maximal situation could be handled using two pumps and mostly one pump is enough and the other is spare
- Typically, in WSS, it's advisable to choose next bigger pump from catalogue than the design parameters require to leave some future and exceptional event head room (about 5 m in head and 10 % in flow – remember to account the increased dynamic head for the 110 % flow!)
- Pressure sewers require sufficient velocity: 0.7–1.5 m/s with one pump one
- In WSS unit head losses are more important than velocities: recommended value is 1–5 m/km, max 8–10 m/km (flow velocities 0.1–0.8 m/s)
- Outlet pressure or pressure anywhere along line shouldn't exceed 80 m or fall under 10 m
- Pressure sustaining or reducing valves if necessary

CASE: DESIGNING A PRESSURE BOOSTER STATION – OR NOT





- A pressure booster station design was ordered
- The WSS was modeled, and based on the model, it was apparent, that just opening a valve at the North-West corner of network suffice to fix pressure problems
- In the end, no pressure booster station was designed – the best possible optimization!

LEARNING OUTCOMES

- Name pump parts and describe centrifugal pump working principle
- Explain characteristic curve and list three most important curves
- Describe how pump speed control works and affinity laws related to it
- Calculate pump energy use
- Calculate/estimate pump flow (demand estimate) and head

PUMP MODELING EXERCISE

- Open base model.fwat file in Fluidit Water (no DEM, ok settings, some colors available)
- Let a system consist of two reservoirs: **A with head of 100 m** and **B with head 130 m**
- Water is pumped from A to B using a centrifugal pump P
- There's a **4000 m long 315PVC pipe between A and P** and **3000 m long 225PEH17 pipe between P and B**
- There's **an consumer half way between A and P**, that consumes on average 10 l/s of water with pattern WEEKDAY
- All junctions have **elevation of 60 m**

- Your tasks
  - Model the system
  - What is the pump head range, if the pump pumps 110 m3/h?
  - How much Grundfos CR120-2 pump would produce flow? (create single point pump curve with working point 120 m3/h x 45 m and single point efficiency curve with 120 m3/h and 75 %)
  - How much flow the same pump produces when running on a) 45 Hz and b) 40 Hz? (set initial speed to 0.9 and 0.8 respectively)
  - How the situation changes, if the 225PEH17 is made bigger, say 280PEH17?