Orroville Dam Weir Orifice

Jeremy D. Bricker
CiTG 3.96
j.d.bricker@tudelft.nl

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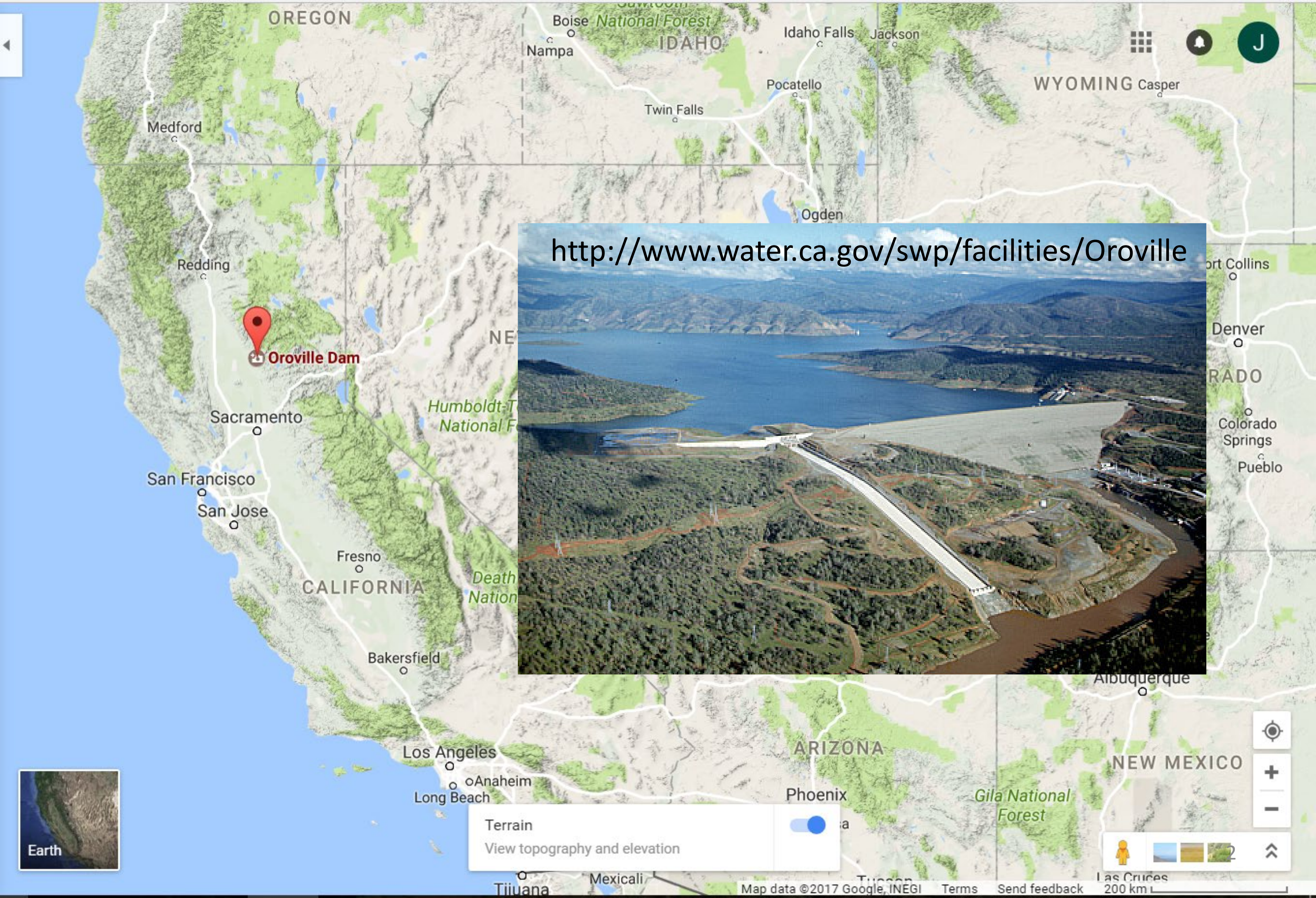
4TU. Resilience Engineering

THIS RESOURCE IS PART OF 4TU RE OER

Urban Resilience

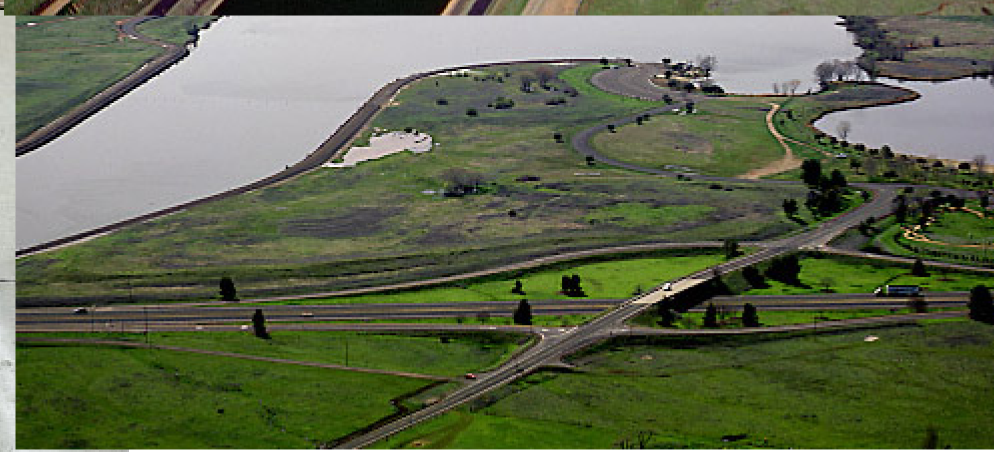
Oroville Dam, tallest in US at 230 m



http://www.water.ca.gov/swp/facilities/Oroville





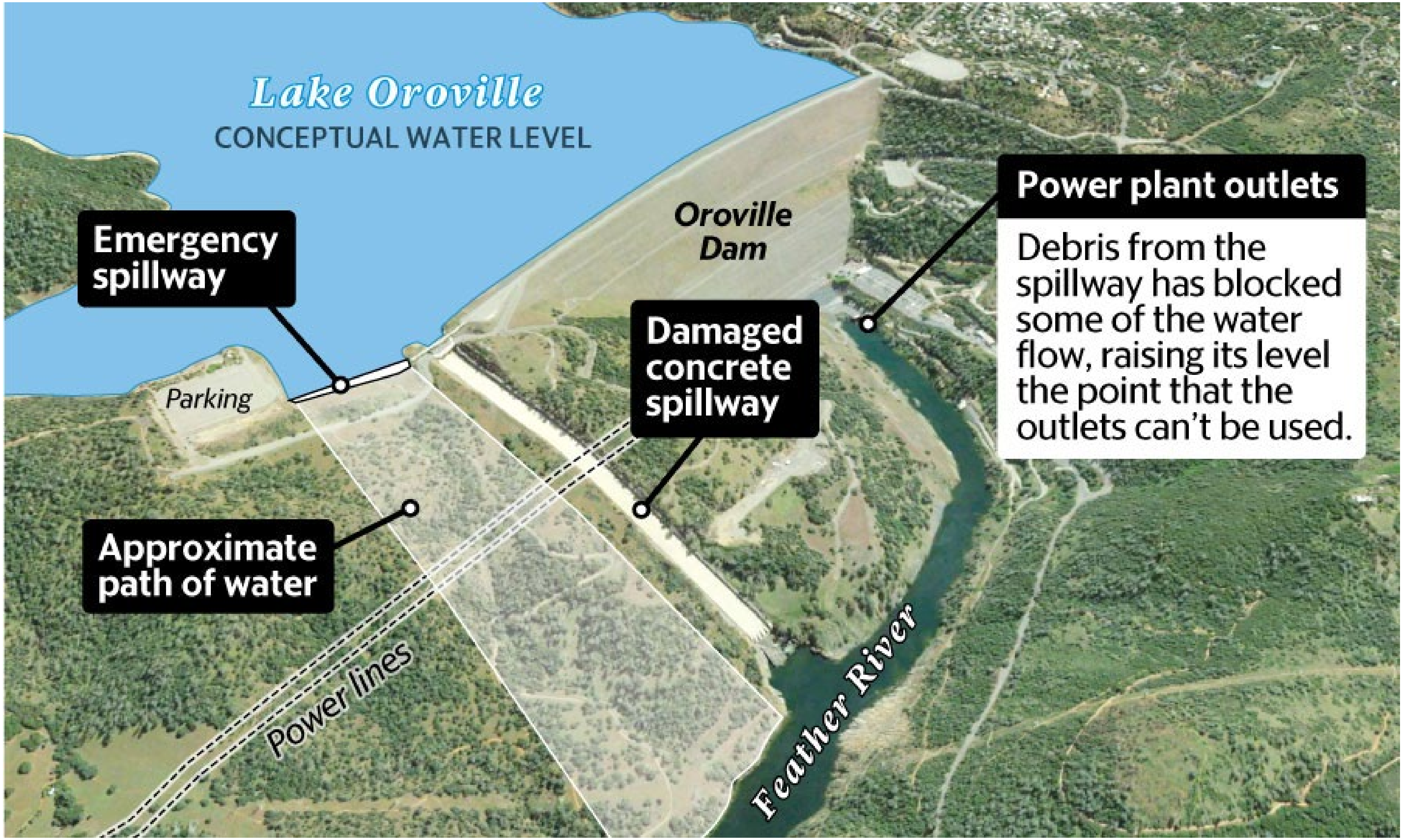


Orovillo – Thermolito PSPP

- Oroville – Thermolito complex generates about 2.8 TWhr/year
- Hyatt PSPP generating capacity 819 MW
  - Underground
  - Design head 187 m
  - 3 dedicated turbines
  - 3 reversible pump/turbines
  - Max flow 480 m^3/s
- Thermalito Diversion PP capacity 3.3 MW
  - Design head 20 m
  - 1 turbine
  - Max flow 17 m^3/s
- Thermalito PSPP capacity 120 MW
  - Design head 29 m
  - 1 dedicated Kaplan turbine
  - 3 reversible Francis pump/turbines
  - Max flow 493 m^3/s

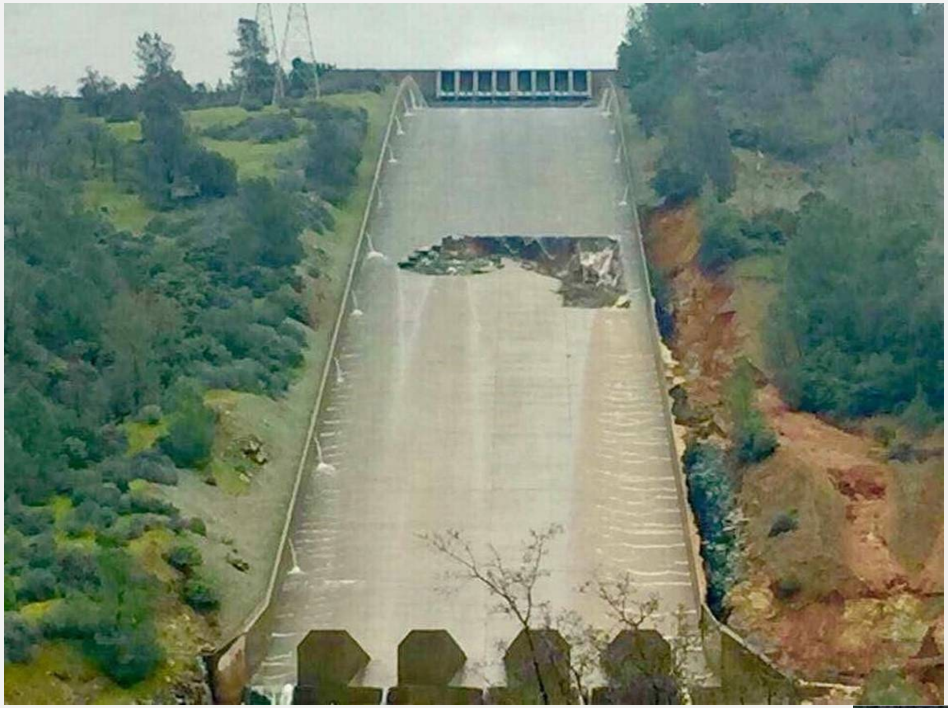
http://www.water.ca.gov/swp/facilities/Oroville

Spillways



www.sacbee.com

Concrete erosion in main spillway Feb 2017 (seen while main spillway gates shut)



www.sacbee.com

The dam was built in the 1960's, and is just reaching the end of its 50 year design life.

Cnbc.com

Cracks in concrete found during inspection 10 years ago were patched.

Erosion


Houston Chronicle

Continued erosion of concrete and underlying earth threatened power lines. Headcutting could eventually threaten spillway gates. To prevent this, main spillway flow reduced, lake level raised to utilize emergency spillway. Powerplant tailrace blocked by concrete debris, so unusable without backwater flooding of powerplant.

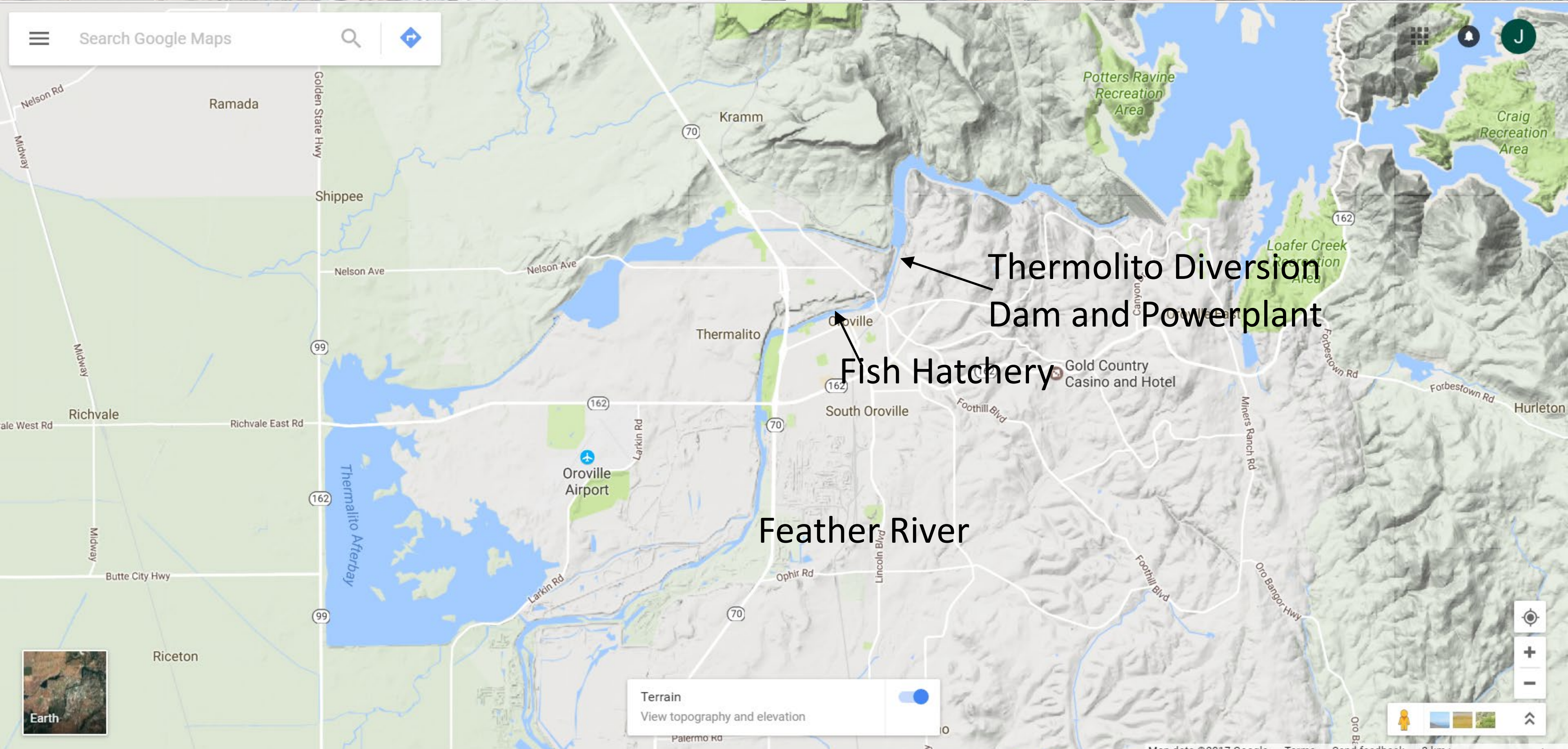
Sfgate.com

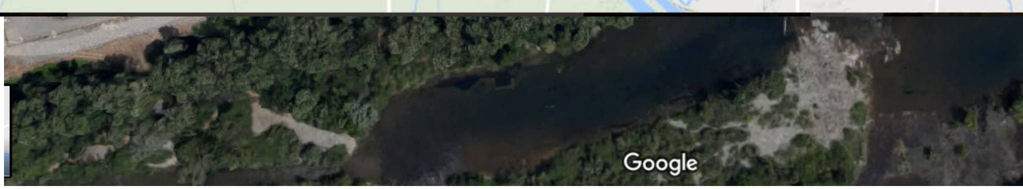
Fish hatchery

- Hatchery fish needed to be rescued from turbid Feather River discharge

https://www.youtube.com/watch?v=15ztuZx6GNA

https://www.reddit.com/r/orovilledam/comments/5z2sln/flooding_at_the_oroville_fish_hatchery_february_9/





http://www.westcoast.fisheries.noaa.gov/stories/2017/21_0321201_oroville_dam_fish_save.html

Headcutting threatening emergency spillway too

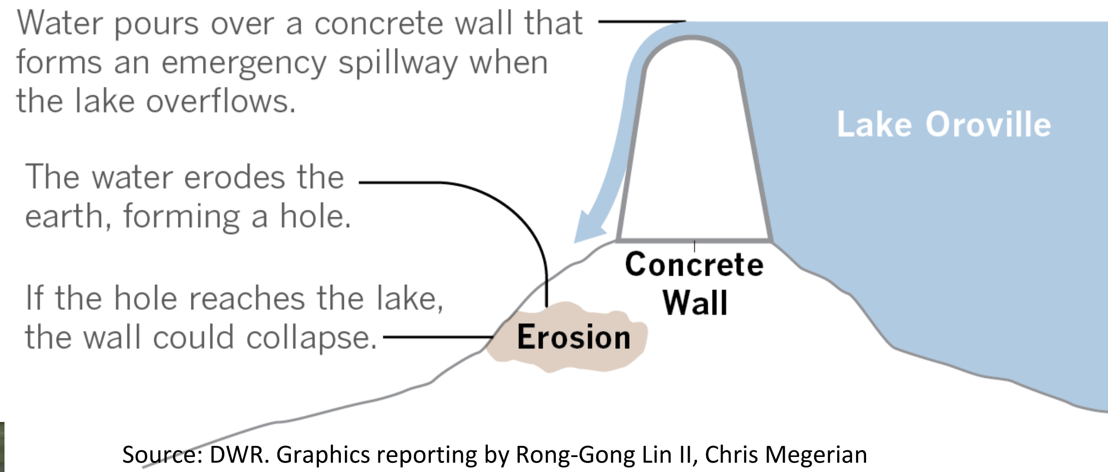
Emergency spillway operation

Weather underground

Progression of headcutting

San Jose Mercury News

Headcutting threatening emergency spillway too



Source: DWR. Graphics reporting by Rong-Gong Lin II, Chris Megerian

(AP Photo/Rich Pedroncelli)

Downstream flooding and evacuation of 200,000 residents

https://www.nbclosangeles.com/multimedia/Oroville-Dam-Spillway-Damage-Repairs-California-Storm-Water-Flooding-419258184.html

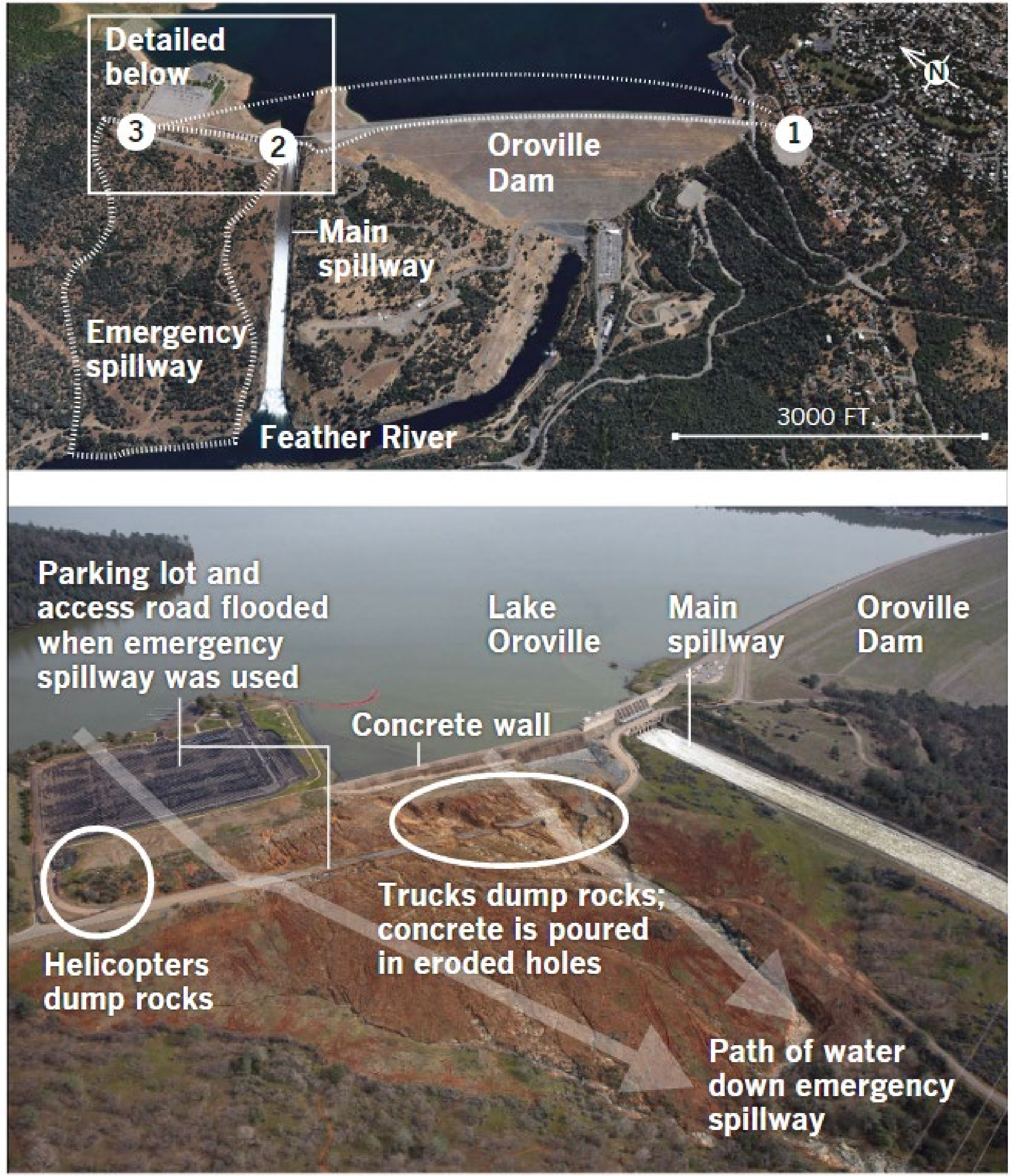
Downstream flooding and evacuation of 200,000 residents

Lake level reduced

- Immediate threat of 10 m emergency spillway weir collapse
- “Lesser of 2 evils”: open main spillway fully and reduce lake level ASAP below emergency spillway
- Water level dropped and emergency spillway overflow ceased
- Repair of scour beneath emergency spillway commenced

Emergency repair of emergency spillway scour

- Race to make spillways stable before next storms arrive
- Quarry trucks stockpile rock at site #1
- Some rock trucked across dam and placed at site #2 with concrete
- Some rock placed by helicopter at site #3



Sources: DWR, Google Earth, detail image courtesy of AFP Getty.
Graphics reporting by Rong-Gong Lin II, Chris Megerian, Brian van der Brug and Paige St. John

Raoul Rañoa/latimesgraphics

Emergency repair of emergency spillway scour

http://www.latimes.com/local/lanow/la-me-ln-inside-race-shore-oroville-dam-20170214-story.html

Continue to drain via main spillway

http://www.latimes.com/local/california/la-me-oroville-spillway-failure-20170216-story.html

Main spillway damage and carved channel

http://www.latimes.com/local/california/la-me-oroville-spillway-failure-20170216-story.html

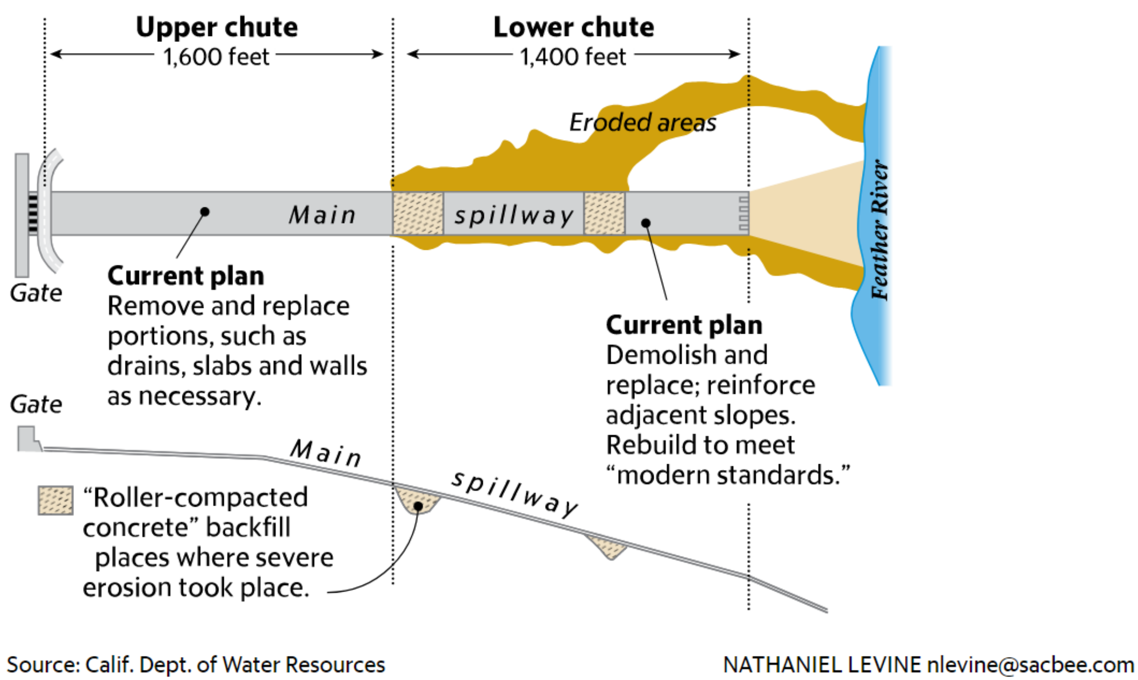
Removing rock/concrete debris from powerplant tailrace canal

Need to remove debris so powerhouse is not flooded by backwater when turbines are operated

http://www.sacbee.com/news/state/california/water-and-drought/article135252184.html

Repair

- Studies show one cause of the main spillway damage was insufficient underdrainage
  - Drains clogged with vegetation and sediments
  - Concrete too thin at drains, with insufficient rebar
  - Uplift forces generated
- Cavitation may also have occurred and damaged concrete
  - Possibly will add aeration slots to redesign
- Emergency spillway: slope will be lined with concrete



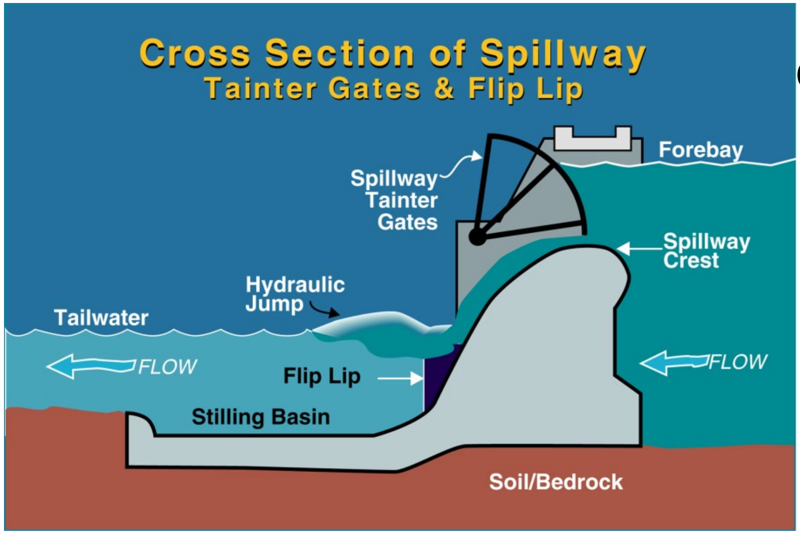
Repair as of April 2018

- https://www.youtube.com/watch?v=hGoVHrBZzKs

CA DWR

How is a spillway designed?

- Orifice or weir equation
- Maximum probable flood must be passed at design reservoir elevation



Gated ogee spillway

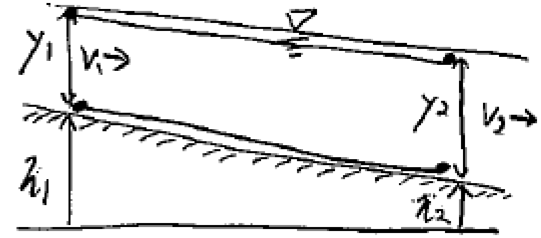
Free ogee spillway

Piano key weir

Morning glory (bell-mouth) spillway

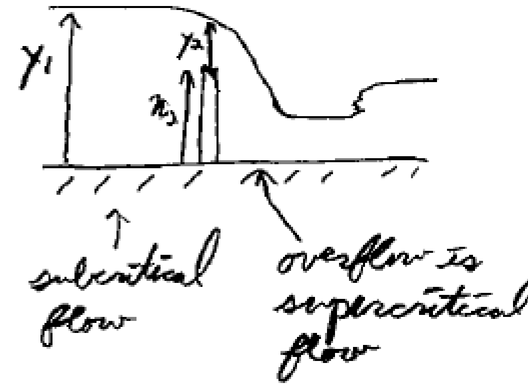
Wikipedia and Worldbank.org

Derive the weir equation

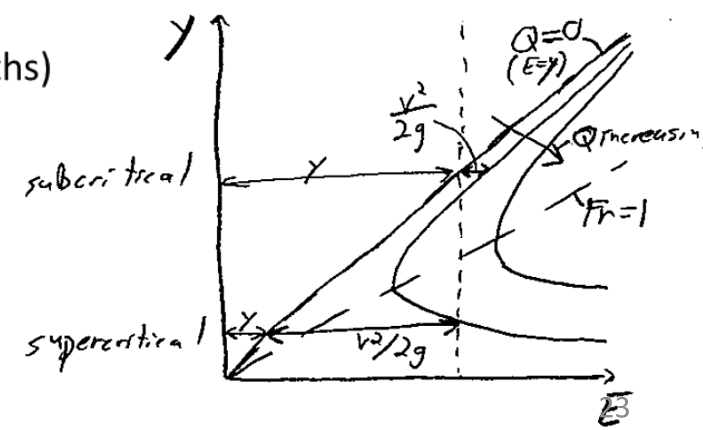


- Apply Bernoulli's equation along a streamline
  - $z \equiv y + \eta$
  - $\left(\frac{p_2}{\rho} + \frac{v_2^2}{2} + gz_2\right) - \left(\frac{p_1}{\rho} + \frac{v_1^2}{2} + gz_1\right) = -\left(\frac{fL}{D} + k\right)\frac{v^2}{2}$
  - For a streamline at the surface $\left(0 + \frac{v_2^2}{2} + g[y_2 + \eta_2\,]\right) - \left(0 + \frac{v_1^2}{2} + g[y_1 + \eta_1\,]\right) = -\left(\frac{fL}{D} + k\right)\frac{v^2}{2}$
  - For a streamline on the bed use the hydrostatic assumption p=ρgy so
    - $\left(\frac{\rho g y_2}{\rho} + \frac{v_2^2}{2} + g\eta_2\right) - \left(\frac{\rho g y_1}{\rho} + \frac{v_1^2}{2} + g\eta_1\right) = -\left(\frac{fL}{D} + k\right)\frac{v^2}{2}$
  - Either way this gives the open channel energy equation
    - $\left(\frac{v_2^2}{2g} + y_2 + \eta_2\right) = \left(\frac{v_1^2}{2g} + y_1 + \eta_1\right) - \left(\frac{fL}{D} + k\right)\frac{v^2}{2g}$
  - Total head $H \equiv \left(\frac{v^2}{2g} + y + \eta\right)$
-

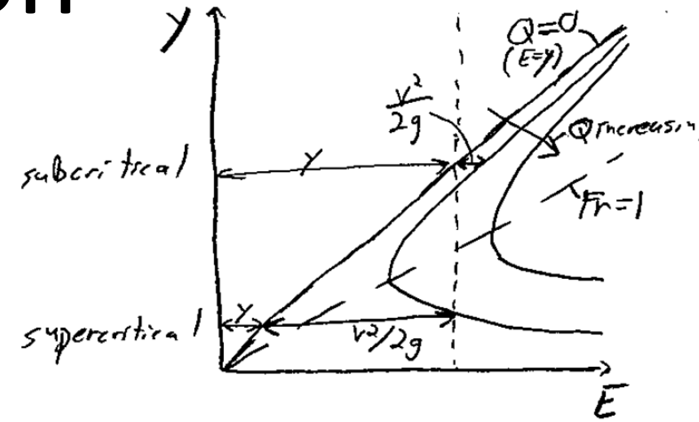
Derive the weir equation



- Free overflow weir, find speed and flowrate
  - Where is flow critical? Use concepts of Specific Head E and Alternate Depths.
  - Total head $H \equiv \left(\frac{v^2}{2g} + y + \eta\right)$
  - Specific head $E \equiv \frac{v^2}{2g} + y$; therefore H=E+ η
  - $Q = vA$; therefore $E \equiv \frac{Q^2}{2gA^2} + y$
  - Assume a rectangular channel of width b, so A=by; therefore $E \equiv \frac{Q^2}{2gb^2y^2} + y$
  - Plot y vs E for constant Q
  - For a given Q and E, 2 possible depths (Alternate Depths)
    - Supercritical: shallow, fast flow
    - Subcritical: slow, deep flow
  - E is minimum when $\frac{dE}{dy} = 0$

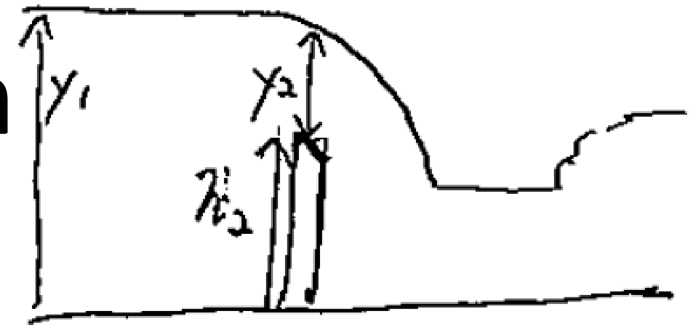


Derive the weir equation



- Find overflow speed and flowrate
  - $\frac{dE}{dy} = 0$ ➔ $\frac{dE}{dy} = \frac{-Q^2}{gb^2y_c^3} + 1 = 0$
  - Critical depth $y_c = \left(\frac{Q^2}{gb^2}\right)^{\frac{1}{3}}$
  - At critical depth, $E_{min} = \frac{Q^2}{2gb^2y_c^2} + y_c = \frac{1}{2}\frac{y_c^3}{y_c^2} + y_c = \frac{3}{2}y_c$
  - Flow speed at critical depth is $v_c = \frac{Q}{A}$
    - From above, $Q^2 = gb^2y_c^3$ and $A = by_c$; therefore $v_c = \sqrt{\frac{Q^2}{A^2}} = \sqrt{\frac{gb^2y_c^3}{b^2y_c^2}} = \sqrt{gy_c}$
    - Critical flow speed $v_c = \sqrt{gy_c}$
  - Define Froude number $Fr \equiv \frac{v}{v_c} = \frac{v}{\sqrt{gy}}$
    - Fr <1 is subcritical; waves can propagate upstream
    - Fr=1 is critical (also called control)
    - Fr>1 is supercritical; waves cannot propagate upstream

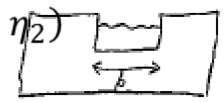
Derive the weir equation

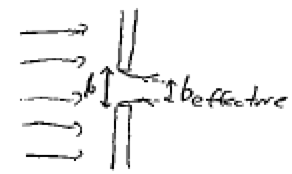


- Find overflow speed and flowrate
  - We found that flow is critical where E=E_{min}. Where does this happen in the figure above?
  - Without friction, H=E+η=constant; therefore $E = E_{min}$ when $\eta = \eta_{max}$.
  - $\eta = \eta_{max}$ and thus critical flow occur on top of the weir crest!
  - Critical flow speed $v_2 = \sqrt{g y_2}$
  - Apply the open channel flow energy equation between sections 1 and 2, assuming no frictional or minor losses, and assume no approach velocity ($v_1 = 0$).
    - $\left(\frac{v_2^2}{2g} + y_2 + \eta_2\right) = \left(\frac{v_1^2}{2g} + y_1 + \eta_1\right)$
    - $\left(\frac{g y_2}{2g} + y_2 + \eta_2\right) = (0 + y_1 + 0)$
    - Flow depth over weir is $y_2 = \frac{2}{3}(y_1 - \eta_2)$;
    - Flow speed over weir is $v_2 = \sqrt{g y_2} = \sqrt{\frac{2}{3} g (y_1 - \eta_2)}$
    - Discharge over weir for an **ideal fluid** is thus is $\boldsymbol{Q = b y_2 v_2 = b g^{\frac{1}{2}} \left[\frac{2}{3}(y_1 - \eta_2)\right]^{\frac{3}{2}}}$
      - where b = weir length
-

Francis Weir Equation

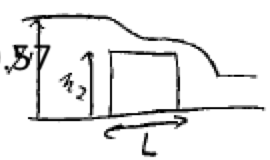
- For a real fluid, the flow equation is
  - $Q = \frac{2}{3} C_1 b \sqrt{2g} (y_1 - \eta_2)^{\frac{3}{2}}$
  - where for a sharp-crested weir, empirically $C_1 = 0.62 + 0.083\left(\frac{y_1 - \eta_2}{\eta_2}\right)$
  - Flow is reduced by end contractions $b_{effective} = b - 0.2(y_1 - \eta_2)$



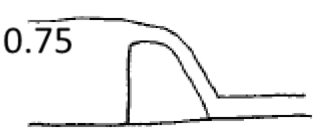


  - Flow is also reduced for submerged weirs $Q_{submerged} = Q_{freeflow}\left[1 - \left(\frac{y_3 - \eta_2}{y_1 - \eta_2}\right)^{\frac{3}{2}}\right]^{0.385}$

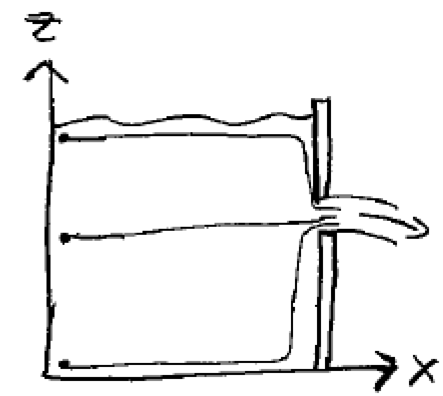
  - For a broad-crested weir with $L > \frac{1}{2}(y_1 - \eta_2)$, the coefficient is $0.5 < C_1 < 0.57$



  - For an ogee spillway, the coefficient is $0.6 < C_1 < 0.75$



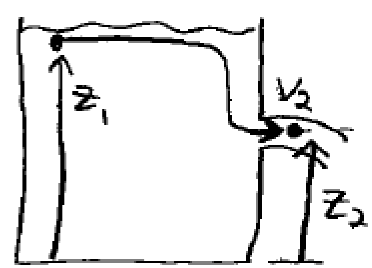
Derive the orifice equation



- Bernoulli equation
  - $\left(\frac{p_2}{\rho} + \frac{v_2^2}{2} + gz_2\right) - \left(\frac{p_1}{\rho} + \frac{v_1^2}{2} + gz_1\right) = -\left(\frac{fL}{D} + k\right)\frac{v^2}{2}$
  - f = Darcy friction factor
  - L = section length
  - D = hydraulic diameter = 4 * (flow area / wetted perimeter)
  - k = minor loss coefficient
  - Assumes
    - Along a streamline
    - No friction
    - Steady flow
    - Incompressible flow

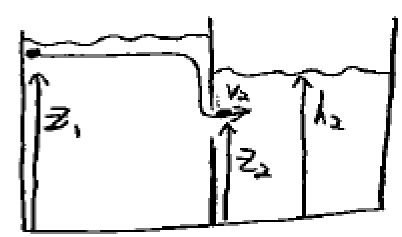
Orifice equation for outlet in air

- Find outlet velocity and flowrate using the Bernoulli equation
- Find outlet velocity and flowrate using the Bernoulli equation
  - $\left(\frac{p_2}{\rho}+\frac{v_2^2}{2}+gz_2\right)-\left(\frac{p_1}{\rho}+\frac{v_1^2}{2}+gz_1\right)=-\left(\frac{fL}{D}+k\right)\frac{v^2}{2}$
- $p_2=0$, $p_1=0$, $v_1=0$, $L=0$
- $p_2=0$, $p_1=0$, $v_1=0$, $L=0$
- $(k-1)=g(z_1-z_2)$
  - $\frac{v_2^2}{2}(k-1)=g(z_1-z_2)$
- Define discharge coefficient
  - Define discharge coefficient $C_v=\frac{1}{\sqrt{k-1}}$
  - $v_2=C_v\sqrt{2g(z_1-z_2)}$
-

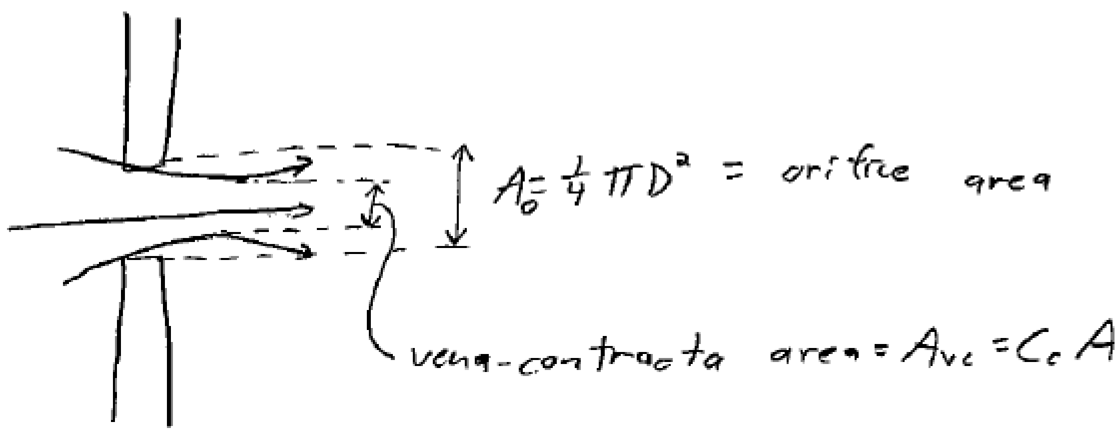


Orifice equation for submerged outlet

- Find outlet velocity and flowrate using the Bernoulli equation
  - $\left(\frac{p_2}{\rho}+\frac{v_2^2}{2}+gz_2\right)-\left(\frac{p_1}{\rho}+\frac{v_1^2}{2}+gz_1\right)=-\left(\frac{fL}{D}+k\right)\frac{v^2}{2}$
- p_1=0, v_1=0, L=0
- For p_2, use the hydrostatic approximation $p_2 = \rho g(h_2 - z_2)$
- Rearrange Bernoulli equation $v_2 = C_v\sqrt{2g(z_1 - h_2)}$
- In general, $v_2 = C_v\sqrt{2g\Delta H}$, where ΔH is the head difference across the opening



Orifice flowrate

- $v = C_v\sqrt{2g\Delta H}$
- $C_c \equiv \frac{Area\ of\ vena\text{–}contracta}{Area\ of\ orifice} = \frac{A_{vc}}{A_0}$
- $Q = vA_{vc} = vC_cA_0 = C_cC_vA_0\sqrt{2g\Delta H}$
- 

Orifice equation discharge and contraction coefficients

Table 17.5 Approximate Orifice Coefficients for Turbulent Water

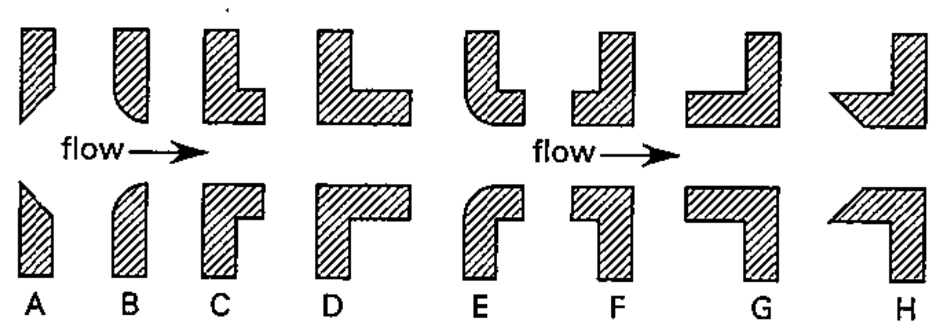


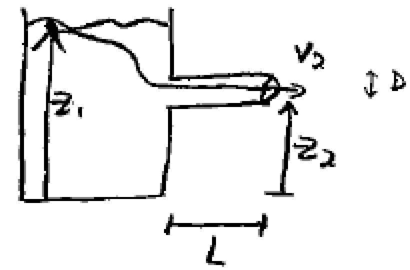
illustration	description	C_d	C_c	C_v
A	sharp-edged	0.62	0.63	0.98
B	round-edged	0.98	1.00	0.98
C	short tube[a] (fluid separates from walls)	0.61	1.00	0.61
D	sharp tube (no separation)	0.82	1.00	0.82
E	sharp tube with rounded entrance	0.97	0.99	0.98
F	reentrant tube, length less than one-half of pipe diameter	0.54	0.55	0.99
G	reentrant tube, length 2 to 3 pipe diameters	0.72	1.00	0.72
H	Borda	0.51	0.52	0.98
(none)	smooth, well-tapered nozzle	0.98	0.99	0.99

[a]A short tube has a length less than 2 to 3 diameters.

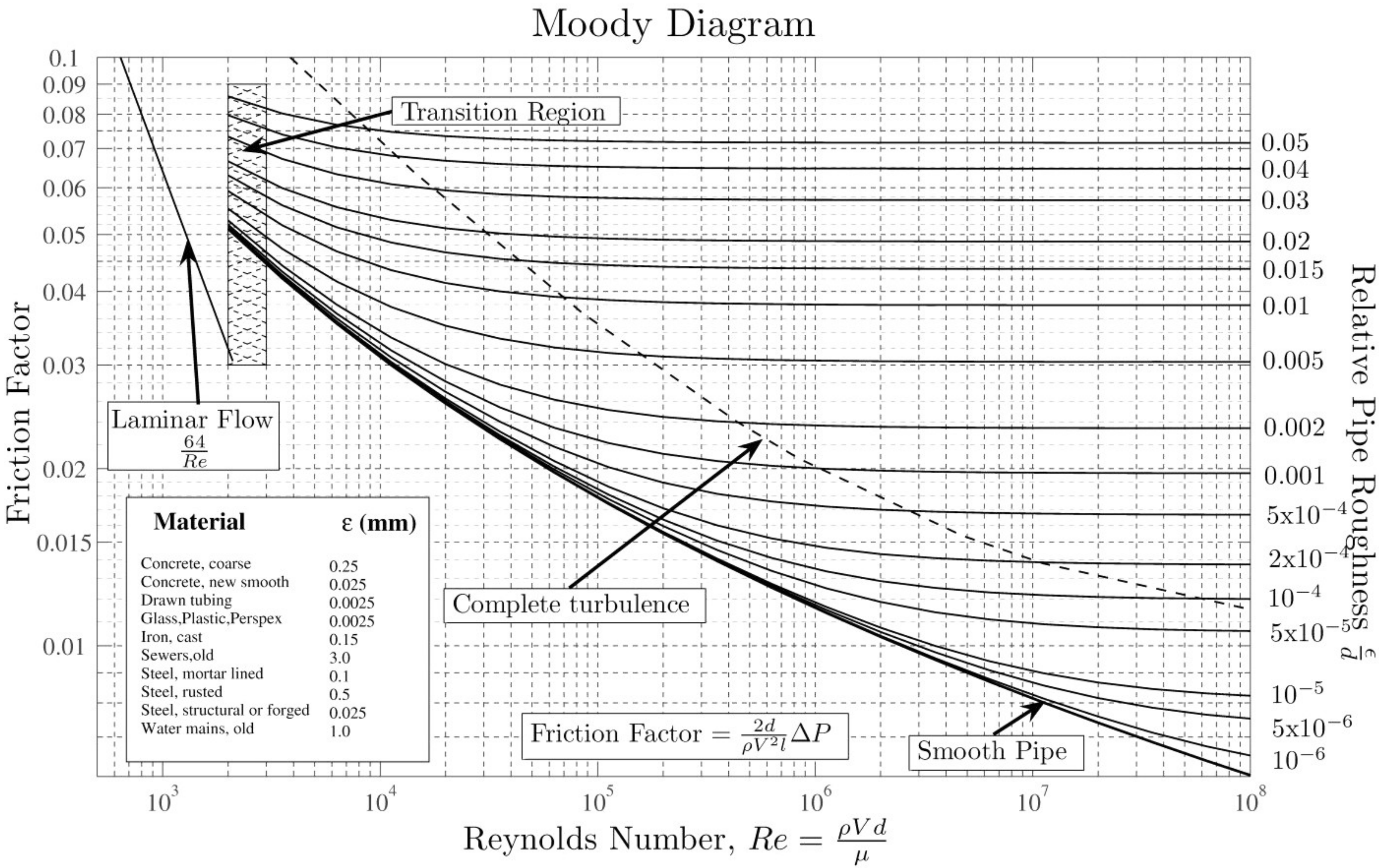
Lindeburg (2006)

Orifice with pipe or tunnel outlet to air

- Bernoulli $\left(\frac{p_2}{\rho}+\frac{v_2^2}{2}+gz_2\right)-\left(\frac{p_1}{\rho}+\frac{v_1^2}{2}+gz_1\right)=-\left(\frac{fL}{D}+k\right)\frac{v^2}{2}$
- $p_2=0$, $p_1=0$, $v_1=0$
- $\left(\frac{v_2^2}{2}+gz_2\right)-(gz_1)=-\left(\frac{fL}{D}+k_{entrance}+k_{exit}\right)\frac{v_2^2}{2}$
  - $K_{entrance}$ and k_{exit} are empirical constants
  - f is the Darcy friction factor
    - For laminar flow, f=64/Re, where the Reynolds number Re=vd/ν, with d the pipe diameter and ν the viscosity in m^2/s.
    - For turbulent flow (Re>2,000), use the Moody diagram or White-Colebrook equations to find f. The Moody diagram shows friction factor as a function of Re, absolute roughness ε, and pipe diameter d.



Moody diagram



Continuity equation

- To keep track of how water level in a reservoir changes in time, use the volume conservation (continuity) equation
  - $\frac{dV}{dt} = \sum(Q_{in} - Q_{out})$ where V=Volume (m^3) and Q=flowrate (m^3/s)
- Discretize explicitly
  - $\frac{V_{t+1} - V_t}{\Delta t} = \sum(Q_{in,t} - Q_{out,t})$
  - Try in MS Excel