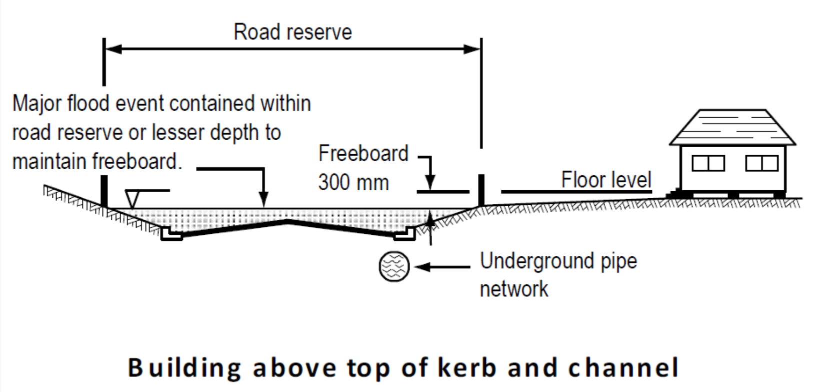
Pipe Network Modelling for Urban Inundation

Bill Syme and Chris Huxley

Today's Presentation Overview

Focus on pipe network modelling for modelling urban inundation

- 1st half on key theory – Bill Syme
- 2nd half on practical and quality control considerations – Chris Huxley



Qld Urban Drainage Manual (QUDM), 2016

Pipe Network Modelling for
Urban Inundation

Theory

Theory Overview

Topics

- Pipe flow regimes
- Energy losses
  - Friction
  - Junctions / Manholes
- Overland flow capture
- Surcharging
- Blockages
- Operational structures

Theory
Some Terminology

Velocities (*V*), for example

- V_i = Velocity in inflow pipe
- V_o = Velocity in outflow pipe

HGL (*H*)

- HGL (Hydraulic Grade Line)
  - Water level (for full pipe, the level in a vertical tube inserted in top of pipe)
- *Total Energy* = $H + V^2/2g$

Energy Loss Coefficient (*K*)

- The fraction of lost kinetic energy ($V^2/2g$)

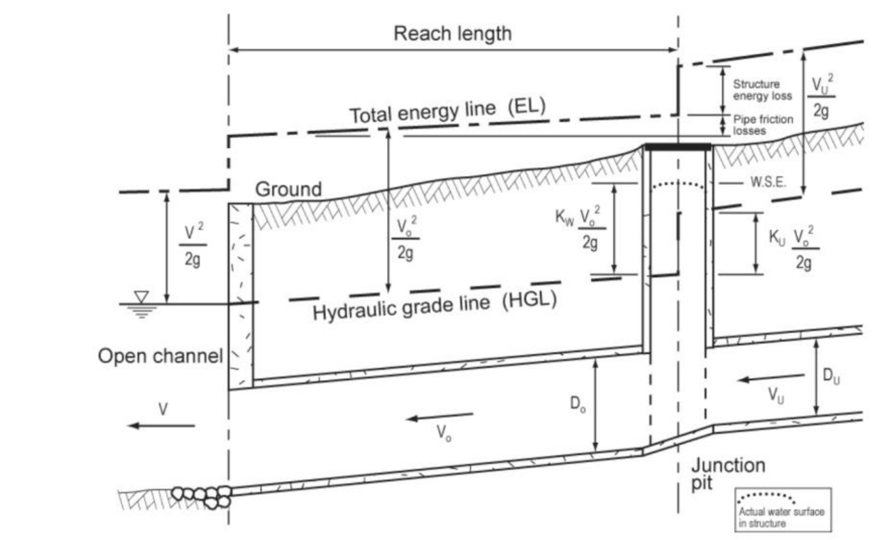


Figure 7.16.1 Qld Urban Drainage Manual (QUDM), 2016

Pipe Flow Regimes
Outlet Controlled

Outlet Controlled Flow Occurs Where

- Downstream water level influences the flow rate
  - Flow is subcritical or pressurised
  - Inlet and outlet energy and friction losses apply

- Free outflow (critical flow) at outlet
  - Inlet energy and friction losses apply

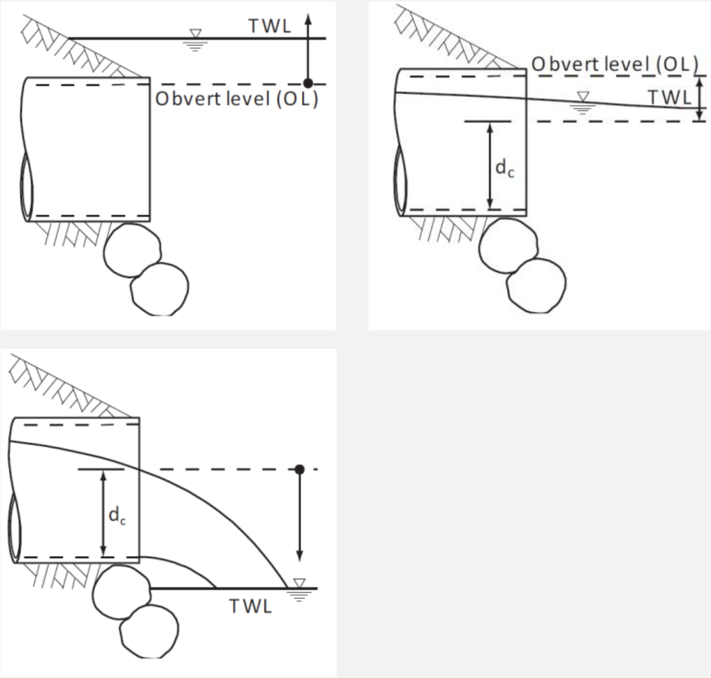


Figure 7.16.2 Qld Urban Drainage Manual (QUDM), 2016

Pipe Flow Regimes
Inlet Controlled

Inlet Controlled Flow Occurs Where

- Inlet conditions control the flow rate
  - Super-critical flow
  - Sufficiently steep to transition into critical flow
  - Orifice flow transitions into critical flow

Note

- Downstream conditions have no affect on flow rate
- Entrance and exit energy losses not applicable

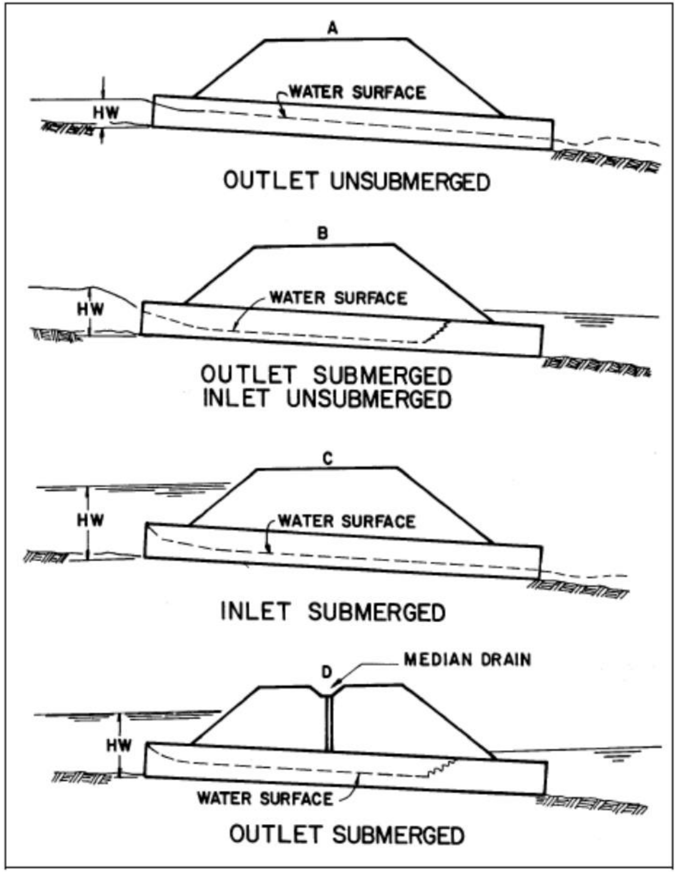


Figure III-1 HEC Hydraulic Design Charts

Friction Energy Losses
Manning's Equation

$$\Delta H_f = S_f L$$

Manning's equation

- $\Delta H_f = \left(\frac{nV}{R^{2/3}}\right)^2 L$ or $Q = \frac{AR^{2/3}}{n}\sqrt{\frac{\Delta H_f}{L}}$
- n is Manning's coefficient; $R = A/P$
- Straightforward calculation when pipe flowing full
  - R is fixed at $\frac{A}{P} = \frac{\pi r^2}{2\pi r} = \frac{r}{2}$
- Pipe partially full – an open channel flow problem (not so straightforward – indeterminate equation)

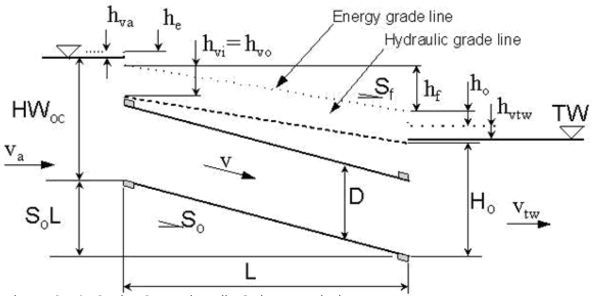


Figure 8-10. Outlet Control, Fully Submerged Flow

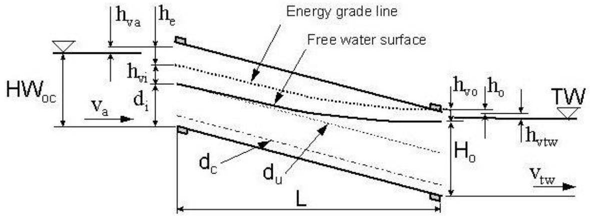


Figure 8-9. Outlet Control Headwater for Culvert with Free Surface

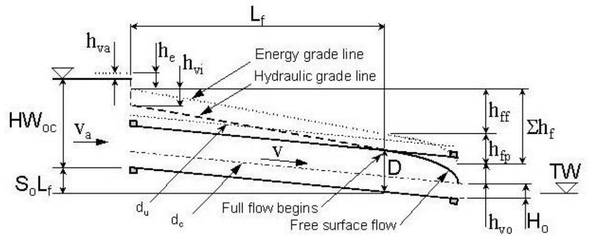


Figure 8-12. Headwater Due to Full Flow at Inlet and Free Surface at Outlet

http://onlinemanuals.txdot.gov/txdotmanuals/hyd/manual_notice.htm

Friction Energy Losses
Manning's n Values

Plenty of guidance in literature

Nature of Surface	Manning's n Range
Concrete Pipe	0.011 – 0.013
Corrugated Metal Pipe	0.019 – 0.030
Vitrified Clay Pipe	0.012 – 0.014
Steel Pipe	0.009 – 0.011
Monolithic Concrete	0.012 – 0.017
Cement Rubble	0.017 – 0.025
Brick	0.014 – 0.017
Laminated Treated Wood	0.015 – 0.017
Open Channels	
Lined with Concrete	0.013 – 0.022
Earth, clean, after weathering	0.018 – 0.020

In: Viessman and Hammer. *Water Supply and Pollution Control, Sixth Edition*. 1998. (Table 6.1) Adapted from: *Design Charts for Open-Channel Flow*. U.S. Department of Transportation, Federal Highway Administration, Hydraulic Design Series No. 3, U.S. Government Printing Office, Washington, D.C. 1961.

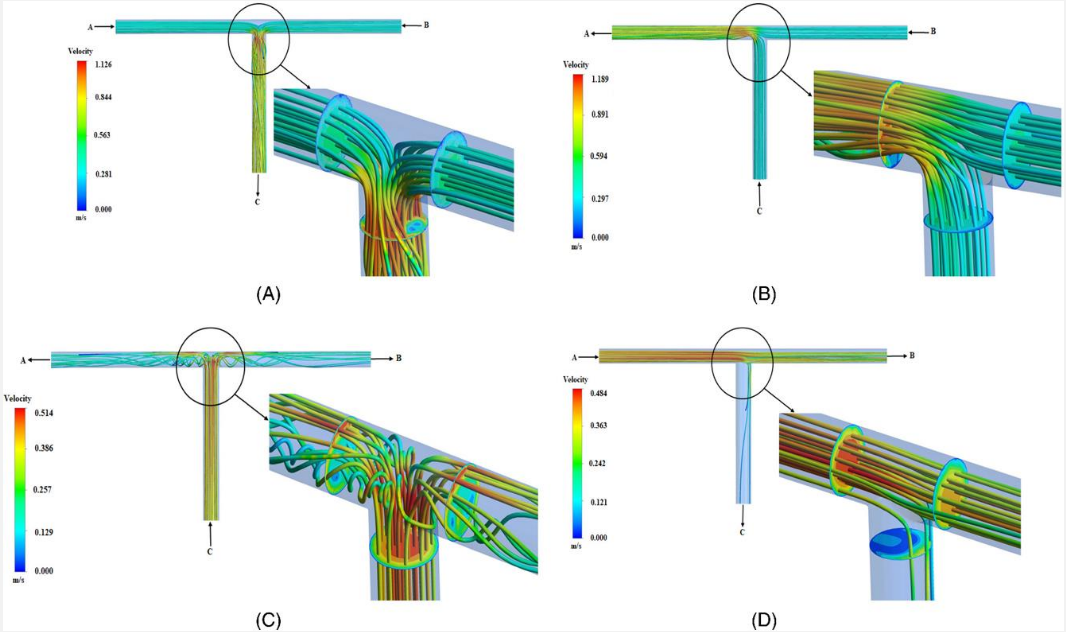
R Pitt, S Clark: Flow in Pipes, Manning's Equation presentation

Kinetic Energy Losses
Manholes, Junctions, Bends, Obstructions

$$\Delta H = K\frac{V^2}{2g}$$

- Fraction (***K***) of kinetic energy loss

Manholes most common
(and most hydraulically complex!)



B.D. Gajbhiye et al, Teaching turbulent flow through pipe fittings using computational fluid dynamics approach, Jan 2020
https://onlinelibrary.wiley.com/doi/10.1002/eng2.12093

Kinetic Energy Losses
Manholes

Primary functions

- Access for construction or maintenance
- Accommodate pipe transitions/changes
- Receive flow from above ground inlets

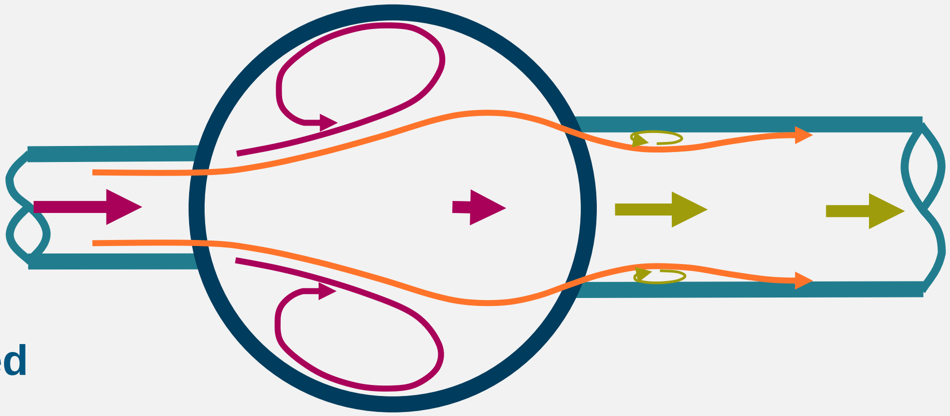
TUFLOW

Kinetic Energy Losses
Manholes

Manhole kinetic energy losses

- Expansion of inlet flows
- Expansion of flow downstream of outlet due to
  - Formation of a vena-contracta in an outlet pipe
  - Discharging into a receiving water body

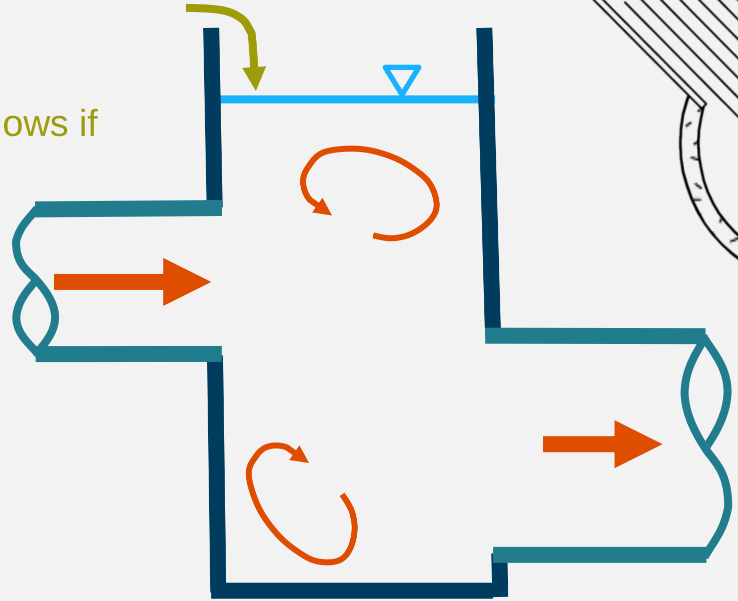
Note: Above energy losses are relevant if a pipe is flowing in an outlet controlled flow regime



Kinetic Energy Losses
Manholes

Additional kinetic energy losses

- Change in horizontal alignment
- Change in vertical alignment
- Other effects such as kerb inlet flows if a significant % of total flow



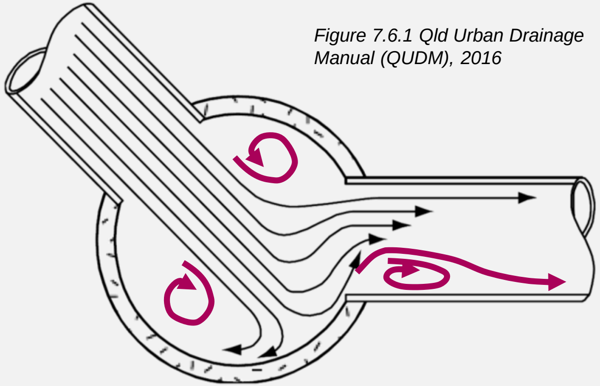
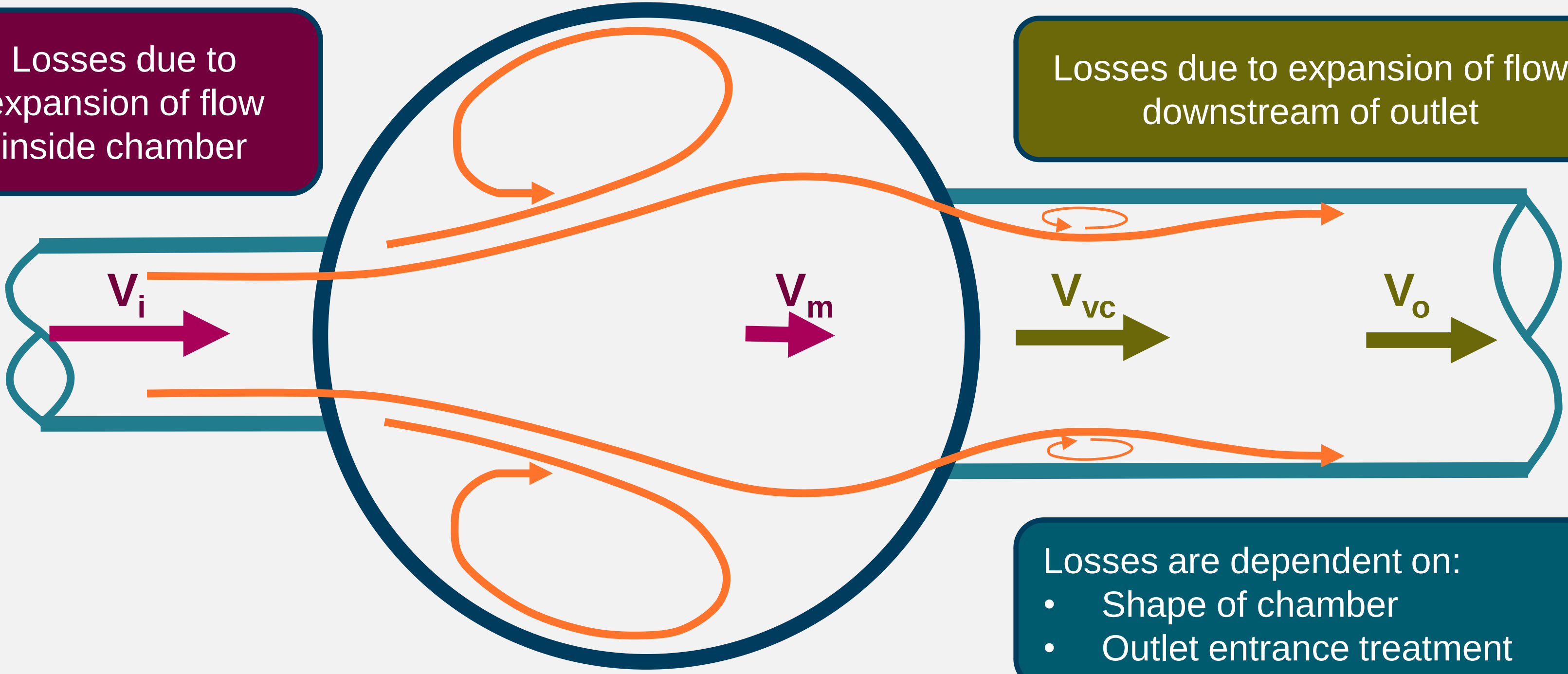


Figure 7.6.1 Qld Urban Drainage Manual (QUDM), 2016

Kinetic Energy Losses
Manhole Inlet and Outlet Losses

Losses due to expansion of flow inside chamber

Losses due to expansion of flow downstream of outlet



Losses are dependent on:
- Shape of chamber
- Outlet entrance treatment

Energy Losses
Manholes – Modelling Approaches

Fix K

- Derived from
  - Desktop calculations
  - Flume or field measurements
- If K varies with flow, not ideal for dynamic simulations
- Plenty of values in the literature
- **Be careful as to which velocity K applies to (Total K usually based on outlet velocity, V_o)**

Vary K according to conditions

- Uses equations for different loss components
- Suits dynamic solutions – recalculate K each timestep

Table 7.16.7 – Energy loss coefficients for flow expansions and contractions within pipes [1]

A_U/A_O or A_O/A_U	d/D	Sharp expansion [2]	Contraction [3]				
			Sharp edge	r/d = 0.02	r/d = 0.04	r/d = 0.06	r/d = 0.1
1	**1.000**	0.000	0.000	0.000	0.000	0.000	0.000
0.8	**0.894**	0.081	0.079	0.058	0.043	0.036	0.027
0.6	**0.775**	0.200	0.248	0.165	0.121	0.091	0.060
0.4	**0.632**	0.377	0.371	0.255	0.187	0.137	0.077
0.2	**0.447**	0.659	0.442	0.324	0.234	0.169	0.086
0.1	**0.316**	0.833	0.471	0.353	0.245	0.180	0.087
0	**0.000**	1.000	0.500	0.376	0.250	0.185	0.087

Notes:

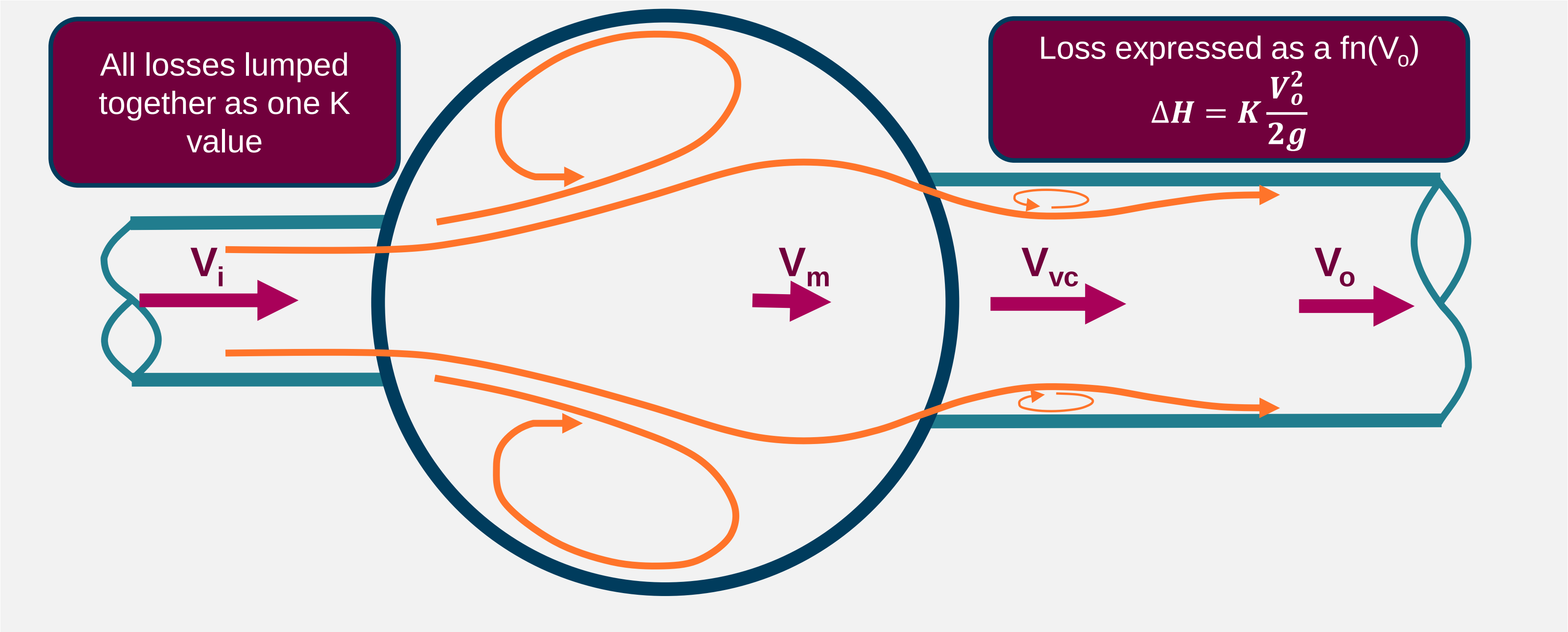
[1] Sourced from Miller (1990).

[2] Energy loss coefficient (K_{exit}) relative to upstream velocity head ($V_u^2/2g$).

[3] Energy loss coefficient (K_{entry}) relative to downstream velocity head ($V_o^2/2g$).

Table 7.16.7 Qld Urban Drainage Manual (QUDM), 2016

Energy Losses
Manholes – Fixed K Approach



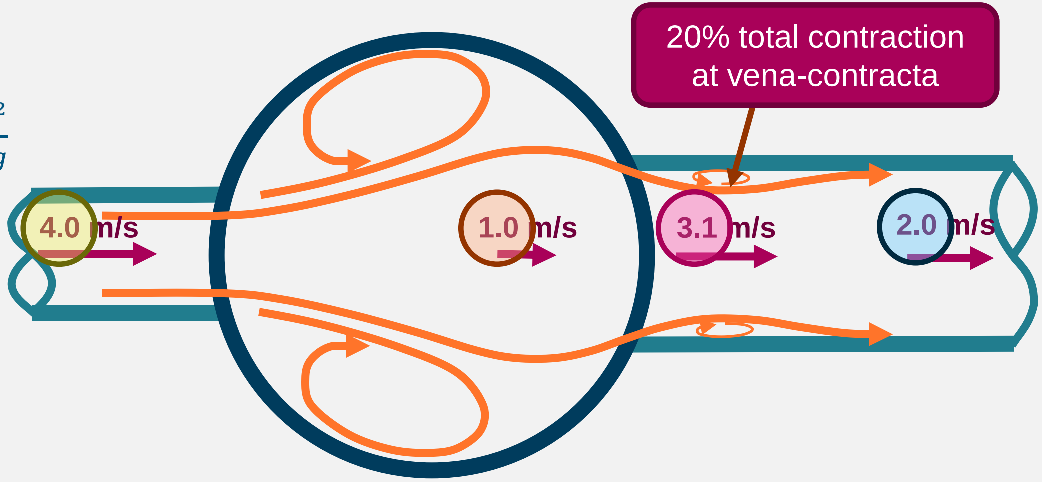
Energy Losses
Manholes – Fixed K Desktop Example

Assuming only inlet and outlet losses (pipes are aligned)

- Expansion loss (derived from first principles) = $\frac{(V_{us}-V_{ds})^2}{2g} = \left(1 - \frac{V_{ds}}{V_{us}}\right)^2 \frac{V_{us}^2}{2g}$
- Inlet loss = $\Delta H_i = \left(1 - \frac{4.0}{1.0}\right)^2 \frac{V_i^2}{2g} = 0.56 \frac{V_i^2}{2g}$
- Outlet loss = $\Delta H_o = \left(1 - \frac{3.1}{2.0}\right)^2 \frac{V_o^2}{2g} = 0.13 \frac{V_o^2}{2g}$

Let's base energy loss on V_o (2 m/s)

- $\Delta H = K \frac{V_o^2}{2g} = \Delta H_i + \Delta H_o$
- $K = \frac{2g}{V_o^2}(\Delta H_i + \Delta H_o) = 0.56 \frac{V_i^2}{V_o^2} + 0.13$
- $K = 2.4$ **(note, K ≠ 0.56 + 0.13)**

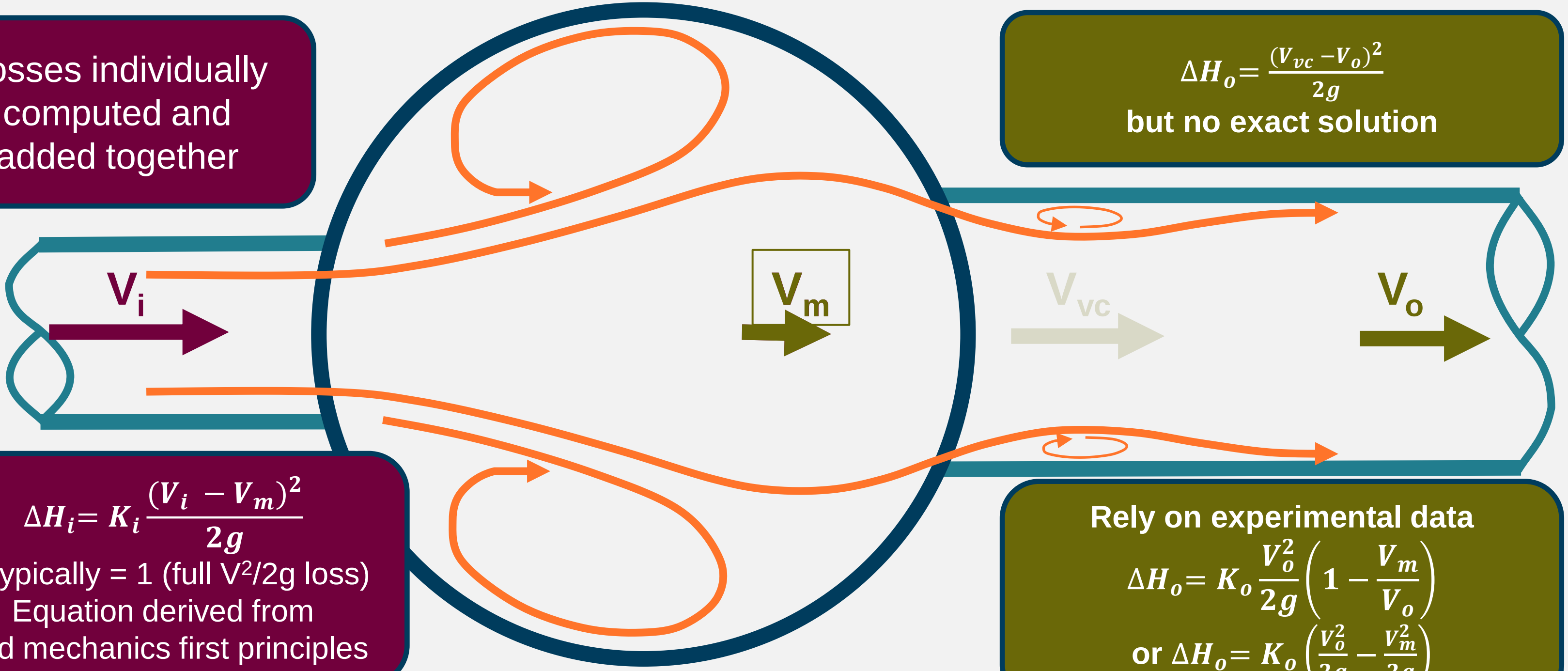


Energy Losses
Manholes – Variable Energy Loss Approach

Losses individually computed and added together

$$\Delta H_i = K_i \frac{(V_i - V_m)^2}{2g}$$

K_i typically = 1 (full $V^2/2g$ loss)
Equation derived from fluid mechanics first principles



$$\Delta H_o = \frac{(V_{vc} - V_o)^2}{2g}$$

but no exact solution

Rely on experimental data

$$\Delta H_o = K_o \frac{V_o^2}{2g}\left(1 - \frac{V_m}{V_o}\right)$$

or $\Delta H_o = K_o \left(\frac{V_o^2}{2g} - \frac{V_m^2}{2g}\right)$

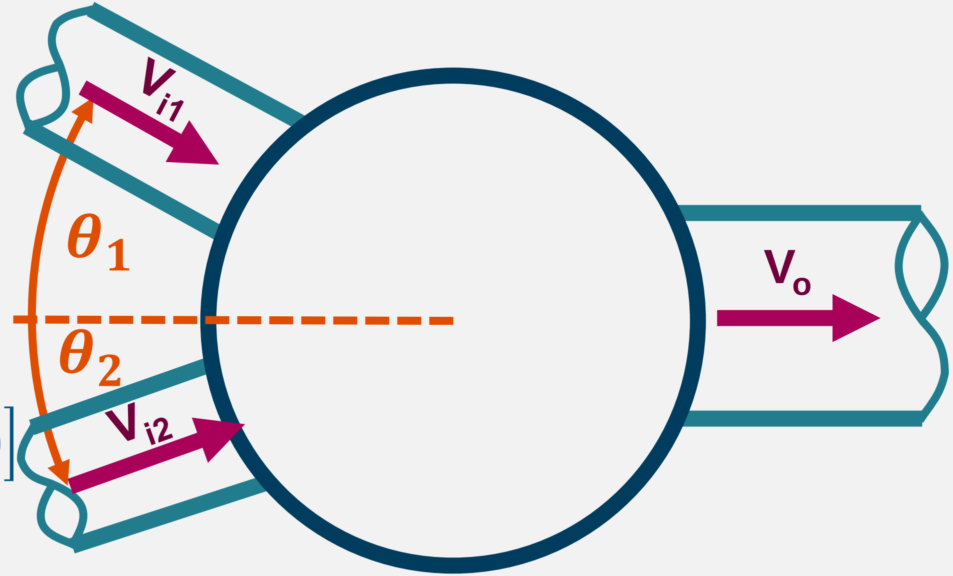
Additional Energy Losses
Manholes – Variable Energy Loss Approach

Unaligned pipe losses

- Angle of approach differs to outflow pipe(s)
- Handles multiple inflow pipes
- $K_\theta = \sum_i \left[f_i \, min\left(\frac{\theta_i^2}{90^2}, 4\right)\right]$
- $f_i = \frac{Q_i}{\sum Q_o}$ (fraction of total flow)

Change in pipe invert elevations

- $K_z = \sum_i \left[min\left(max\left(\frac{f_i(h_o - h_i)(h_0 + y_o - h_i - y_i)}{y_o y_i}, 0\right), 2\right)\right]$



Minimising Energy Losses Manholes

Maintain velocities through manhole

- Keeping chamber size to minimum
- Minimise turbulence/eddies
- Benching

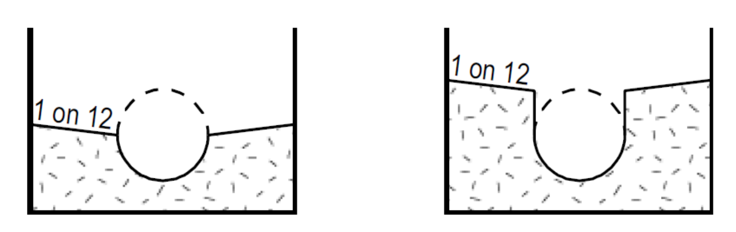


Figure 7.16.4 Qld Urban Drainage Manual (QUDM), 2016

Minimise vena-contracta effect in outlet pipe

- e.g. using Bellmouth entrance

Direct flow to centre of outlet

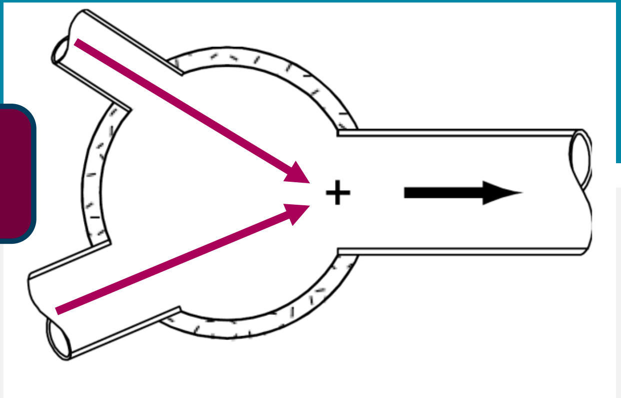


Figure 7.6.2 Qld Urban Drainage Manual (QUDM), 2016

Maximise vena-contracta width (to reduce vena-contracta velocity)

Maximise

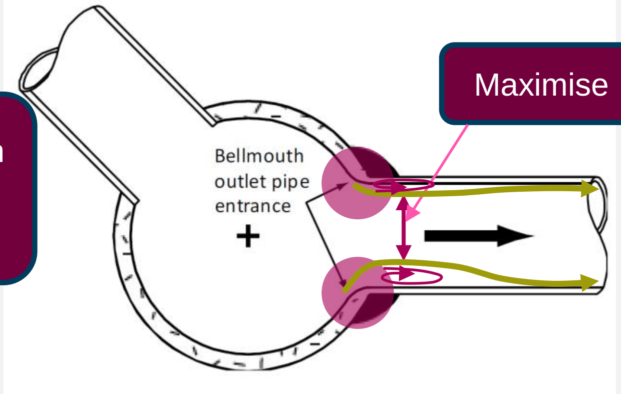


Figure 7.6.3 Qld Urban Drainage Manual (QUDM), 2016

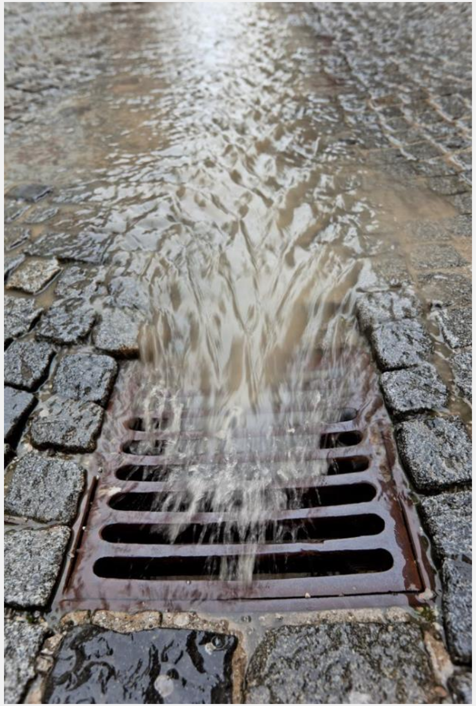
Above Ground Flow Capture Inlets/Pits/Drains/Gully Traps

Captures road or overland flow into pipe network

- Many, many approaches!
- May also backflow or surcharge (intentionally or unintentionally!)

Different terminologies, same function

- Pits
- Inlets / Kerb inlets
- Drains
- Gully traps



Above Ground Flow Capture
On-Grade Kerb Inlets

Drains water from road kerbing

- Flow higher flows, bypass flow occurs (Steeper the road, greater the bypass flow)
- Use approach flow vs capture flow (Q-Q), or depth vs capture flow (y-Q) curves
  - Derived from flume/field measurements or theory
  - Can convert Q-Q to a y-Q curve using Manning's equation

Critical to have accurate representation of above ground depth or approach flow

Grate Flow Curve

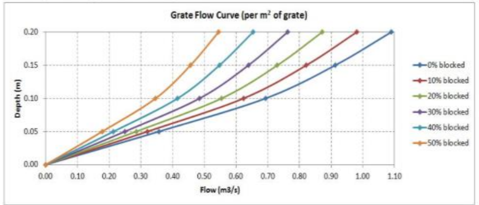
Water Depth (m)	Discharge (m^3/s) per m^2 of grate area					
	0% blocked	10% blocked	20% blocked	30% blocked	40% blocked	50% blocked
0.00	0.000	0.000	0.000	0.000	0.000	0.000
0.05	0.357	0.321	0.285	0.250	0.214	0.178
0.10	0.693	0.624	0.554	0.485	0.416	0.347
0.15	0.913	0.822	0.730	0.639	0.548	0.456
0.20	1.089	0.980	0.871	0.763	0.654	0.545

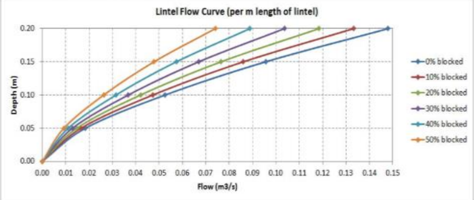
NOTE: Multiply table value by grate area to calculate site specific value

Lintel Flow Curve

Water Depth (m)	Discharge (m^3/s) per m length of lintel					
	0% blocked	10% blocked	20% blocked	30% blocked	40% blocked	50% blocked
0.00	0.000	0.000	0.000	0.000	0.000	0.000
0.05	0.018	0.017	0.015	0.013	0.011	0.009
0.10	0.053	0.047	0.042	0.037	0.032	0.026
0.15	0.096	0.086	0.077	0.067	0.057	0.048
0.20	0.148	0.133	0.118	0.104	0.089	0.074

NOTE: Multiply table value by lintel length to calculate site specific value

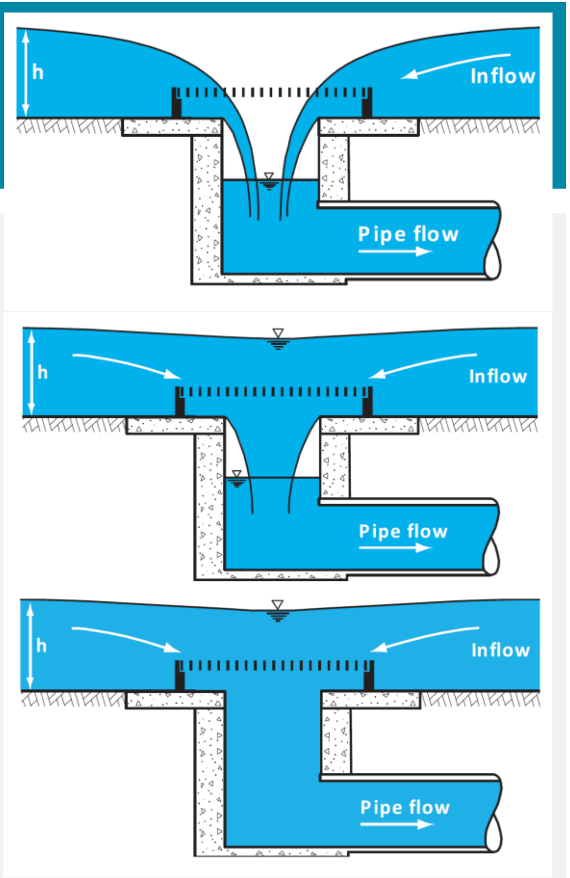




Above Ground Flow Capture
Sag Inlets

Drains ponded water

- Best modelled using depth-discharge relationship
  - Derived from flume/field measurements or theory
- Assume no bypass flow
- High probability of debris impeding flow



Figures 7.5.4, 7.5.5, 7.5.6
Qld Urban Drainage Manual (QUDM), 2016

Flow Surcharging
Inlet Backflow

Backflow occurs where pipe pressure (head) exceeds ground level

- Often cause of unintentional flooding

Causes

- Pipe design capacity exceeded
  - Which maybe the intended design, for example
    - Pipes designed for 1 in 10 AEP
    - Roadways and overland flow paths > 1 in 10 AEP
- Blockage in the pipe network
- Backflow from receiving waters
  - River in flood or elevated tidal levels

May need different y-Q curve to capture flow

- If ground flooded, backflow flow rate may be controlled by ground flood depth

Flow Surcharging
Manhole Lid Popping

Manhole lid popping

- Usually unintended – pressure exceeds downward forces
- Suddenly causes backflow
- Modelling requires conditions around when lid will pop

https://www.youtube.com/watch?v=1Wtdhfzb-Yg

https://www.youtube.com/watch?v=e9WuH0NcLE8

Blockages

Major problem, managed via

- Trash racks and gross pollutant traps
- Debris deflectors
- Maintenance programs

Table 7.5.1 – Provision for blockage at kerb inlets

Inlet type	Blockage factor	
	Design value [1]	Severe conditions [2]
Sag kerb inlets:		
Kerb inlet	20%	100 %
Grated	50 %	100%
Combination	[3]	100%
Continuous (on-grade) kerb inlets:		
Kerb inlet	20%	100%
Longitudinal bar grated	40%	100%
Transverse bar grate or longitudinal bar grate incorporating transverse bars	50%	100%
Combination	[4]	100%
Field (drop) inlets:		
Flush mounted	80%	100%
Elevated (pill box) horizontal grate	50%	100%
Dome screen	50%	100%
Open pipe inlets (blockage factors as per culverts)	Refer to Table 10.4.1	

Table 7.5.1 Qld Urban Drainage Manual (QUDM), 2016

(After) 2007 Flood, Newcastle

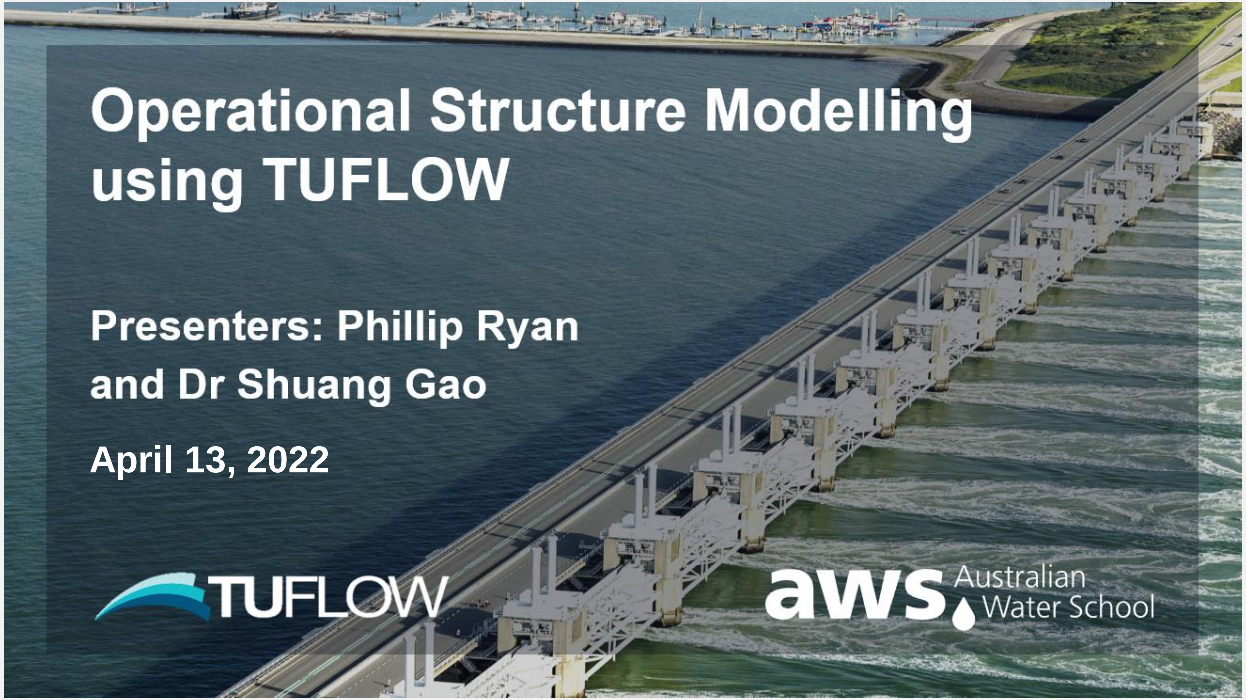
Toowoomba, 2011 (news.com.au)

Operational Structures

Example

- Backflow prevention devices
- Pumps
- Gates

Upcoming Webinar



Pipe Network Modelling for
Urban Inundation

Hands-on Modelling
Quality Control
Discussion / Demonstration