Accurate modelling of the hydraulic grade line by recursive discretization of pipes presenting background leakage

Camille Chambon, Olivier Piller, Iraj Mortazavi

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CCWI 2023 - Oral Presentation

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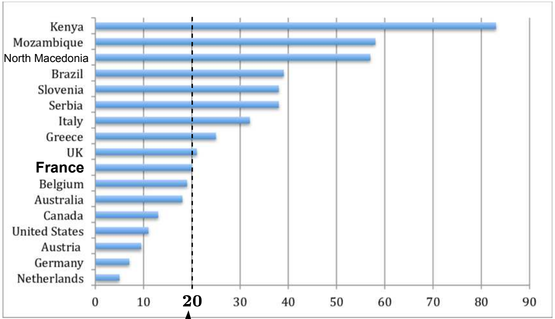
Table of Contents

Background leakages in water distribution networks (WDNs)

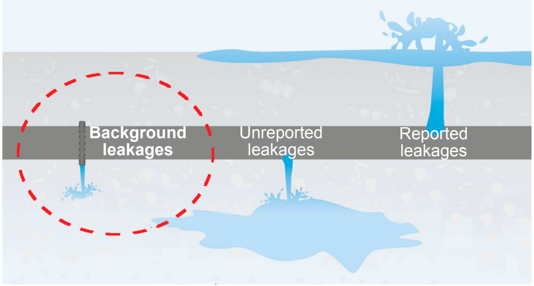
Leakage rates (in %) in WDN around the world (Laspidou, 2014; Lao et al., 2022):



≈ **average leakage rate in the world**

Leakages in WDNs ⇒
- Huge **water losses**
- **Undermined** service quality (Almandoz et al., 2005)
- **Waste** of energy (Colombo et al., 2002)

Different **types** of **leakages** (Farley, 2001; Thronon et al., 2008):

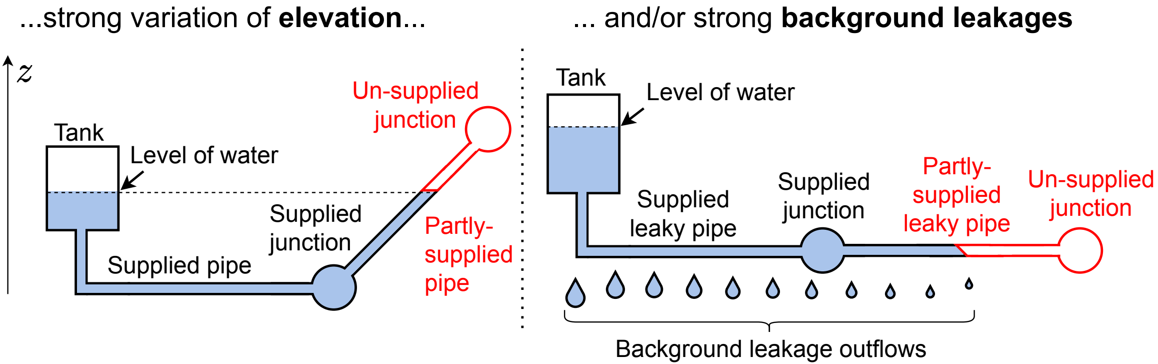


<u>Background leakages</u>:

- come from **slight** outflows from **joints**, **fittings** and thin **cracks**
- appear because of **wear** and **aging** of the networks
- are
  - **below** detection **threshold** of measuring instruments
  - **continuous** and last for a **long time**
  - **pressure dependent**

High-lying nodes and partly-supplied pipes

High-lying node and **partly-supplied pipe** can appear in case of...



⇒ neglecting them can lead to **miscomputation** of the hydraulic grade lines (**HGLs**).

Existing solutions: e.g., Piller and van Zyl (2010)

Problem: existing solutions do not take into account of high-lying nodes and **partly-supplied pipes** in WDNs subject to **background leakage outflows**.

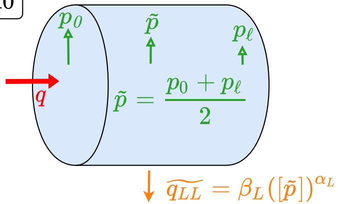
Table of Contents

Direct models to simulate **pressure-dependent** background leakages

Friction head-loss ξ_f computed from **1** flow rate q ...

... and lineic outflow of **background leakages** $\widetilde{q_{LL}}$ computed from **1** pressure head $\tilde{p}$:

M0



With:

- α_L : type of leakages
- β_L : level of degration of the pipe

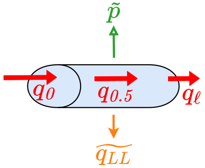
(Germanopoulos, 1985; Giustolisi et al., 2008)

$$\Rightarrow \partial q / \partial x = 0, \forall x \in [0, \ell]$$

... or ξ_f computed from **3** flow rates q_0 , $q_{0.5}$ and q_ℓ ...

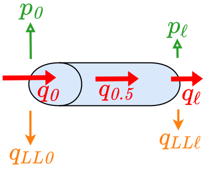
... and $\widetilde{q_{LL}}$ computed from $\tilde{p}$:

M1



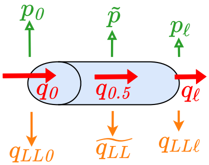
... or q_{LL0} and $q_{LL\ell}$ computed from p_0 and p_ℓ :

M2



... or q_{LL0} , $\widetilde{q_{LL}}$ and $q_{LL\ell}$ computed from p_0 , $\tilde{p}$ and p_ℓ :

M3



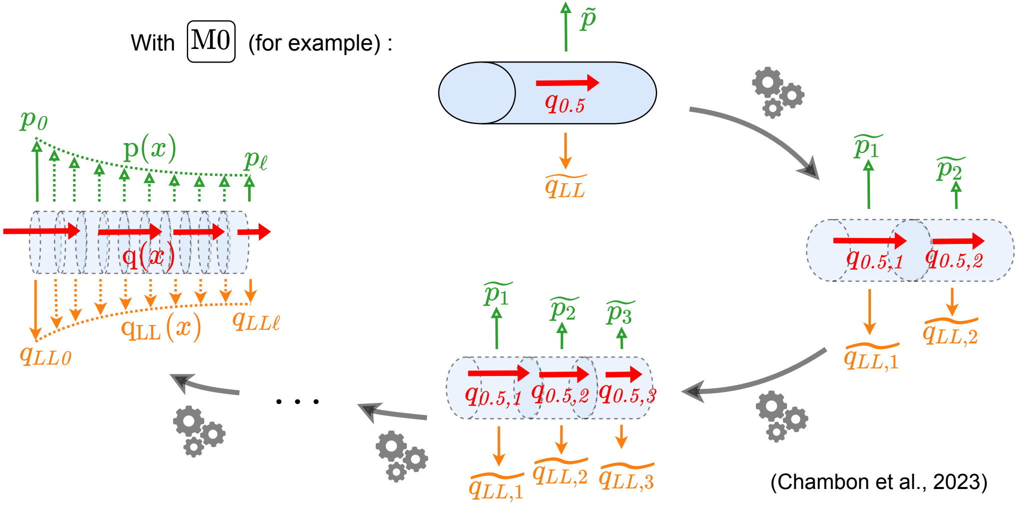
(Chambon et al., 2023)

$$\Rightarrow \partial q / \partial x \neq 0, \forall x \in [0, \ell]$$

Iterative model of background leakages

Model $\boxed{\text{Ref}}$: based on any of $\boxed{\text{M0}}$, $\boxed{\text{M1}}$, $\boxed{\text{M2}}$ or $\boxed{\text{M3}}$, and on a **recursive discretization algorithm**

With $\boxed{\text{M0}}$ (for example) :

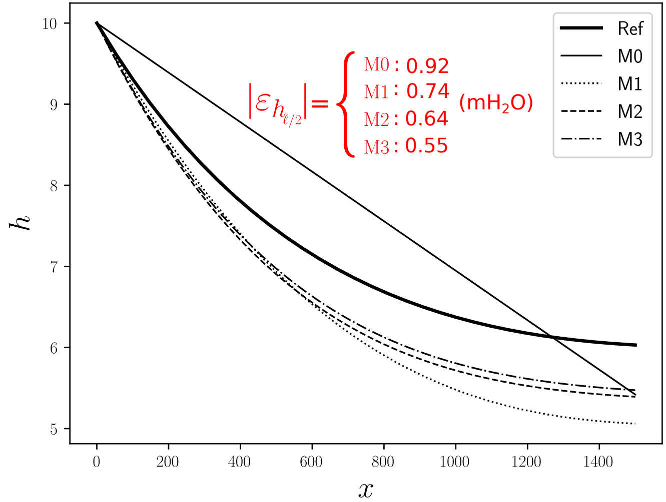


(Chambon et al., 2023)

$\Longrightarrow$ **Very good approximation** of the theoretical **HGL**

HGLs along a single leaky pipe **without high-lying node**

Same leakage parameters $\alpha_L = 1.5$ and $\beta_L = 10^{-3}\,\mathrm{l\,s^{-1}\,m^{-1-\alpha_L}}$ for all models $\{\mathrm{M0}, \ldots, \mathrm{M3}\}$:



⇒ models $\{\mathrm{M1}, \mathrm{M2}, \mathrm{M3}\}$ compute **better predictions** of heads than $\mathrm{M0}$, especially at **intermediate positions**

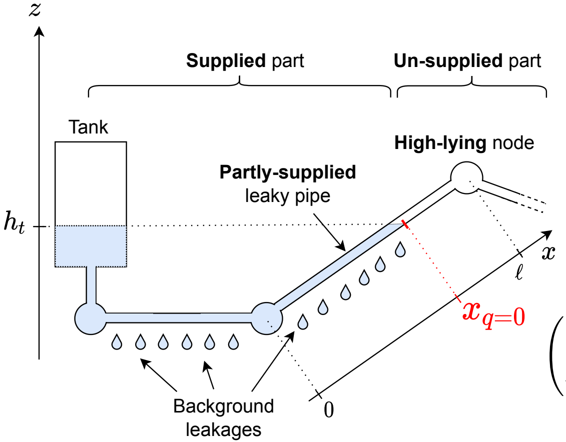
(Chambon et al., 2023)

Table of Contents

Handle **high-lying** nodes and **partly-supplied** pipes

Method: use one of $\{\mathrm{M1}, \mathrm{M2}, \mathrm{M3}\}$, flow rates correction and pipe discretization.

Step 1: in each pipe, **find** the position $x_{q=0}$ (if it exists) at which the flow rate becomes zero:



… then, in each pipe where $x_{q=0}$ exists, use it to **correct** the flow rates at pipe's extremities:

$$\begin{cases} \widetilde{q_0} = q_{0.5} + \int_{\ell/2}^{x_{q=0}} \mathrm{q_{LL}}(x)\,\mathrm{d}x \\ \widetilde{q_\ell} = 0 \end{cases}$$

… finally, **solve** for all flow rates $\boldsymbol{q_{0.5}}$ and heads at junctions $\boldsymbol{h}$ in the whole system at equilibrium, using the corrected $\widetilde{q_0}$ and $\widetilde{q_\ell}$ in each pipe where $x_{q=0}$ exists:

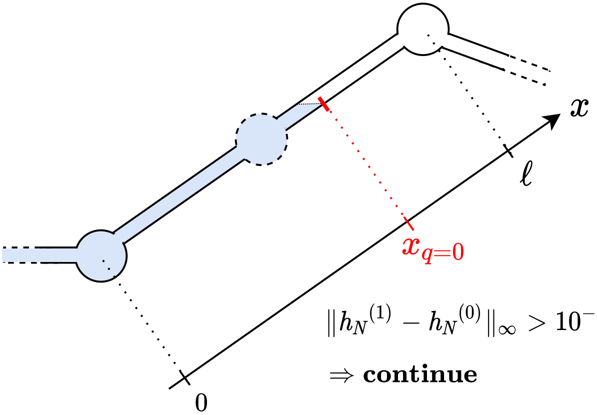
$$\begin{pmatrix} \boldsymbol{\xi_f}(\boldsymbol{q_{0.5}}, \boldsymbol{h}) - \boldsymbol{A}^T \boldsymbol{h} - \boldsymbol{A}_0^T \boldsymbol{h_0} \\ \boldsymbol{A}^- \widetilde{\mathbf{q}_\ell}(\boldsymbol{q_{0.5}}, \boldsymbol{h}) - \boldsymbol{A}^+ \widetilde{\mathbf{q}_0}(\boldsymbol{q_{0.5}}, \boldsymbol{h}) - \mathbf{c}(\boldsymbol{h}) \end{pmatrix} = \boldsymbol{0},$$

with $\boldsymbol{A} = \boldsymbol{A}^+ - \boldsymbol{A}^-$

Step 2: **discretize** the pipes into sub-pipes using the discretization algorithm from Chambon et al. (2023). Then,

1. **find** in each sub-pipe the position $x_{q=0}$ (if it exists) at which the flow rate becomes zero,
2. **correct** flow rates $\widetilde{q_0}$ and $\widetilde{q_\ell}$ at the extremities of each sub-pipe,
3. **solve** for $\boldsymbol{q_{0.5}}$ and $\boldsymbol{h}$ in the discretized system

as at step 1, and check for **convergence** of the discretization algorithm.



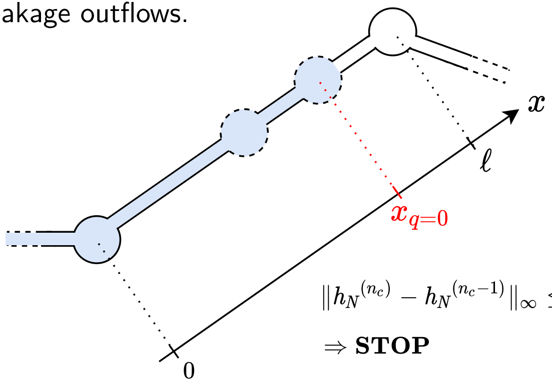
$$\|h_N{}^{(1)} - h_N{}^{(0)}\|_\infty > 10^{-3} \text{ mH}_2\text{O}$$

$\Rightarrow$ **continue**

Steps 3, 4, 5, ...: **repeat** the same process as at step 2, until convergence of the discretization algorithm.

At **convergence** of the discretization algorithm:

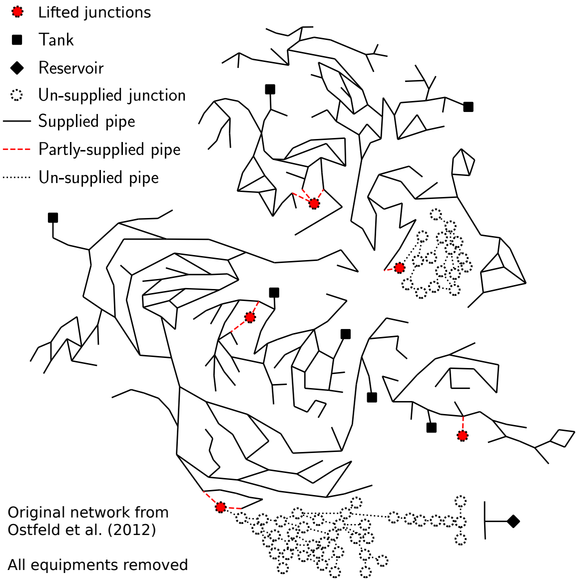
- all sub-pipes are either **fully-supplied** or **fully-unsupplied**
- last computed $x_{q=0}$ is the **correct** end-position for integration of $\mathrm{q_{LL}}(x)$,
- values of $\boldsymbol{q_{0.5}}$ and $\boldsymbol{h}$ in the discretized system are **very good approximations** that take into account of hygh-lying nodes, partly-supplied pipes and pressure-dependent background leakage outflows.



$$\|h_N^{(n_c)} - h_N^{(n_c-1)}\|_\infty \leq 10^{-3}\ \mathrm{mH_2O}$$

$\Rightarrow$ **STOP**

Application to a network with lifted junctions and background leakages



Original network from Ostfeld et al. (2012)

All equipments removed

$\Rightarrow$ the detected **un-supplied** junctions and **partly-supplied** pipes are **consistent** with the initially lifted nodes

Global demand satisfaction
- Before application: $99\,\%$
- After application: $88\,\%$
- Absolute difference: $\mathbf{-11}\,\%$

Cumulated leakage outflow
- Before application: $52.03\,\mathrm{l\,s^{-1}}$
- After application: $41.35\,\mathrm{l\,s^{-1}}$
- Relative difference: $\mathbf{-21}\,\%$

$\Rightarrow$ **significant differences** before and after application of the method.

Integration into the framework **OOPNET**

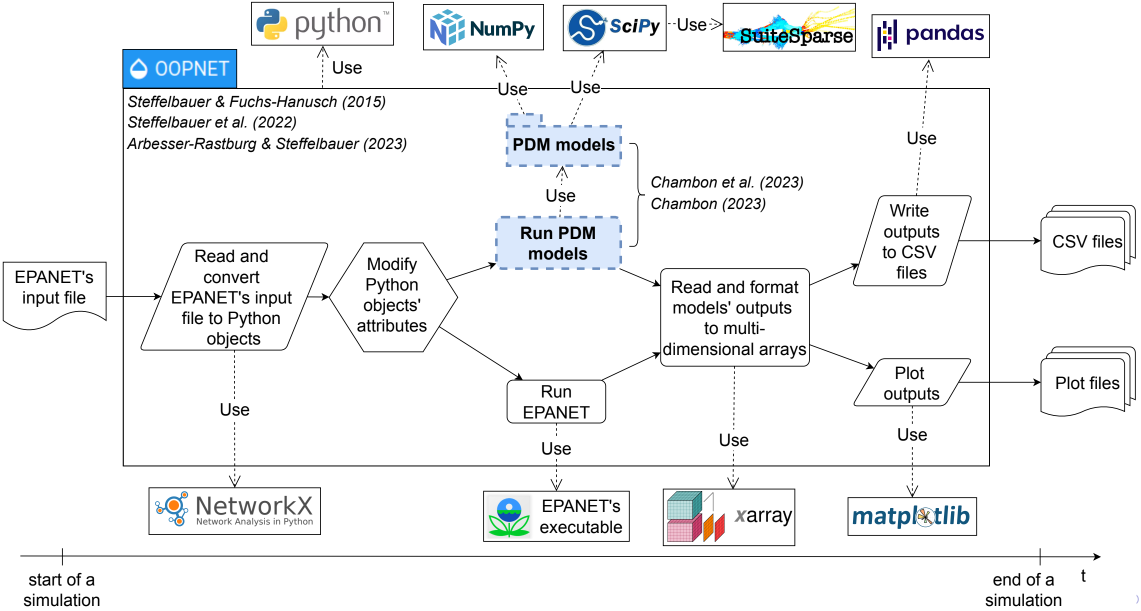


Table of Contents

Conclusions

⇒ A new **extended period simulator** (EPS) of **pressure-dependent** background leakages

⇒ Detects and handles **high-lying nodes** and **partly-supplied pipes** in deficient networks

⇒ Coded in **Python**, and integrated into the framework **OOPNET** (see `https://github.com/oopnet/oopnet`)

⇒ Contribution to deciding of the **best strategies** for **optimal functioning** and rehabilitation of the WDNs, and to reducing **water losses**

Thank you for your attention!

Acknowledgements :

The work presented here is part of the French research project ROC (oriented renewal of pipes) that is funded by the ERDF, the Nouvelle Aquitaine region, the Loire-Bretagne and Adour-Garonne water agencies, and the ARS Aquitaine.

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Appendix: analytical calculation of $x_{q=0}$ for models $\{\mathrm{M1}, \mathrm{M2}, \mathrm{M3}\}$

- For $\mathbf{M1}$: $r^{\mathrm{M1}} = \dfrac{q_{0.5}}{\widetilde{q_{LL}}} + \dfrac{\ell}{2}$, with $\widetilde{q_{LL}} = \mathrm{q_{LL}}(\widetilde{p}) \Rightarrow x^{\mathrm{M1}}_{q=0} = r^{\mathrm{M1}}$ if $0 < r^{\mathrm{M1}} < \ell$

- For $\mathbf{M2}$: solve $\mathrm{q}^{\mathrm{M2}}(x) = q_{0.5} - q^{\mathrm{M2}}_{LL}(\dfrac{x + \ell/2}{2}) \cdot (x - \dfrac{\ell}{2}) = 0$ for $\{r^{\mathrm{M2}}_1, r^{\mathrm{M2}}_2\}$ using the quadratic and Viète's formulas (Weisstein, 1999, p. 1479)

  Then, $$x^{\mathrm{M2}}_{q=0} = \begin{cases} \min\limits_{i\in\{1,2\}} \left(\left\{ r^{\mathrm{M2}}_i \mid r^{\mathrm{M2}}_i \in \,]0,\ell[\, \right\}\right) & \text{if } q_{0.5} \geq 0, \\ \max\limits_{i\in\{1,2\}} \left(\left\{ r^{\mathrm{M2}}_i \mid r^{\mathrm{M2}}_i \in \,]0,\ell[\, \right\}\right) & \text{otherwise.} \end{cases}$$

- For $\mathbf{M3}$: idem $\mathbf{M2}$, but using Cardano's formula (Weisstein, 1999, p. 364-365).

  Then, $$x^{\mathrm{M3}}_{q=0} = \begin{cases} \min\limits_{i\in\{1,2,3\}} \left(\left\{ r^{\mathrm{M3}}_i \mid r^{\mathrm{M3}}_i \in \,]0,\ell[\, \right\}\right) & \text{if } q_{0.5} \geq 0, \\ \max\limits_{i\in\{1,2,3\}} \left(\left\{ r^{\mathrm{M3}}_i \mid r^{\mathrm{M3}}_i \in \,]0,\ell[\, \right\}\right) & \text{otherwise.} \end{cases}$$