Pollution-based model predictive control of combined sewer networks, considering uncertainty propagation

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2. Case Study
3. Methodology
4. Results and Discussion
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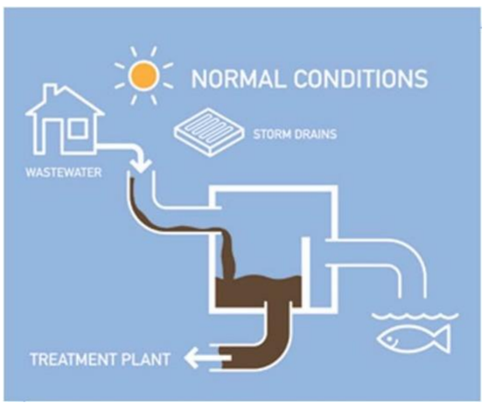
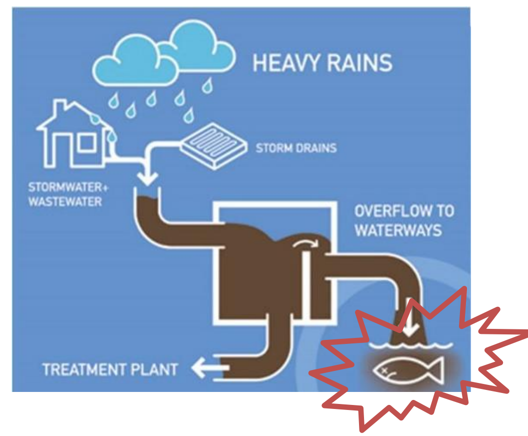
Introduction

Combined Sewer Network

Dry weather flow (DWF)



Wet weather flow (WWF)



Pollution Risk

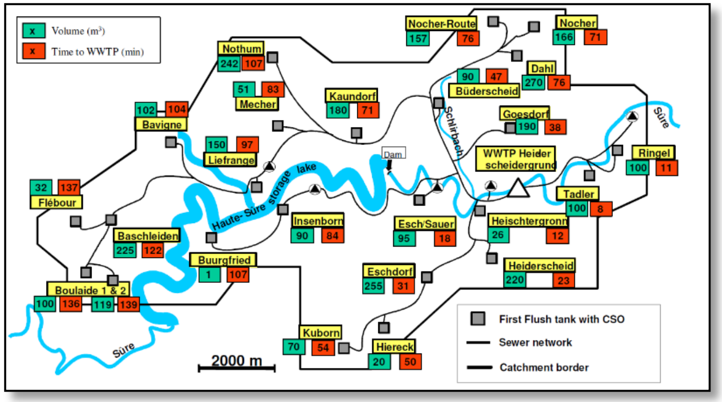
Source: http://whenitrains.commons.gc.cuny.edu/

Real-time control (RTC)

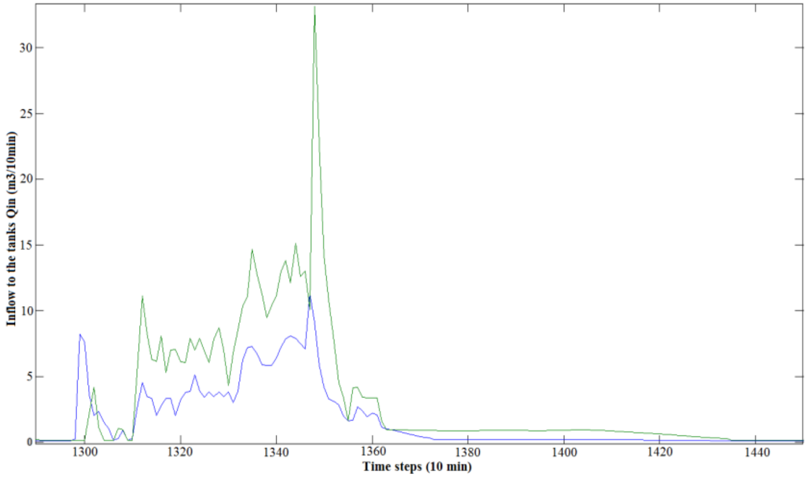
- Wastewater quantity and quality
- Fast (simple) model
- Uncertainty analysis
- No modification on the physical network

Case Study

- ❑ **Haute-Sûre catchment, Luxembourg**
- Location: Northwest of Luxembourg.
- Capacity: 12000 population equivalents (PE). Future Plan: 24 Sub-catchments with 24 CSO tanks.
- In this research **only two** of CSO tanks are considered to test the controllers



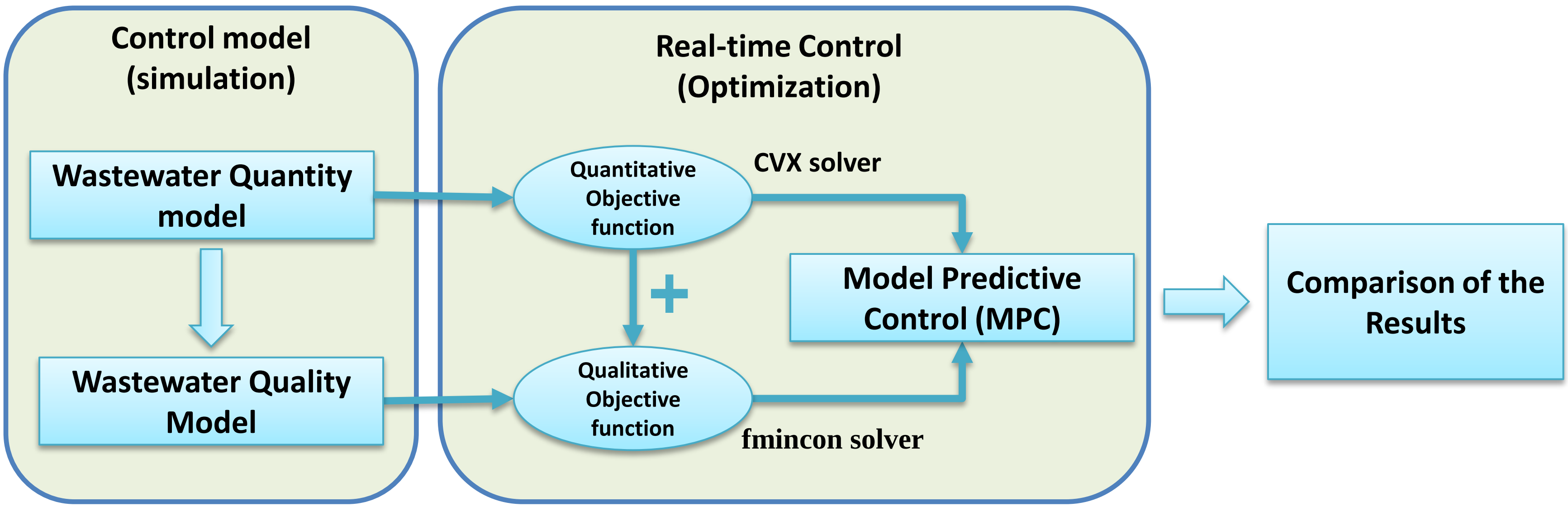
Haute-Sûre catchment (D. Fiorelli, G. Schutz, 2009)



Measured inflow to the tanks
during the October 2002 rain scenario

Blue: Buderscheid CSO tank
Green: Kaundorf CSO tank

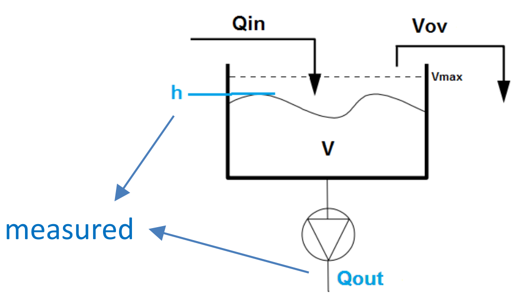
Methodology:



Method: Wastewater Quantity model

Simple tank model:

✓ Based on conservation of volume in the tank.



System variables

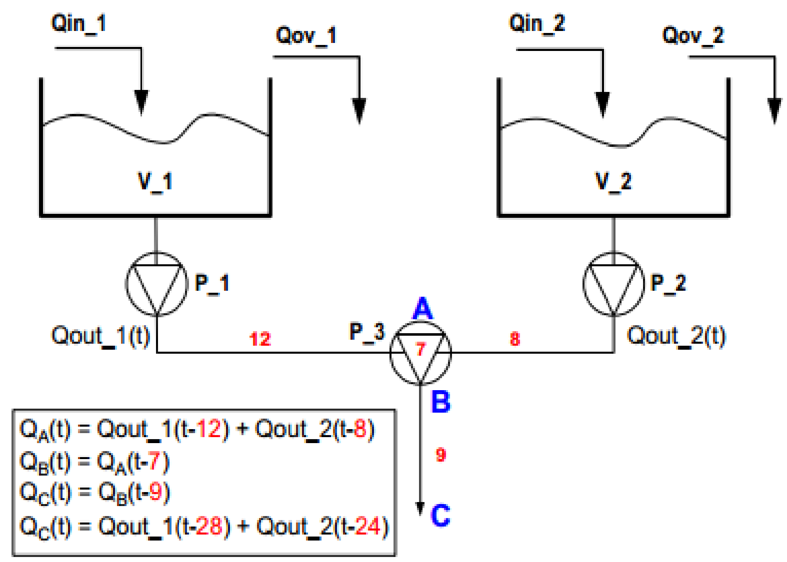
$$V(t) = V(t-\Delta t) + Q_{in}(t)\Delta t - Q_{out}(t)\Delta t - V_{ov}(t)$$

$$Q_{in}(t) = \left(\frac{V(t) - V(t-\Delta t) - V_{ov}(t)}{\Delta t}\right) + Q_{out}(t)$$

$$Q_{in}(t) = Q_{DW}(t) + Q_{WW}(t)$$

The flow in the network:

✓ Modelled using the delay time concept.



Time delay concept used in the network modelling.

h: wastewater level in the tank (measured by sensor)
Qin: inflow
Vov: overflow volume

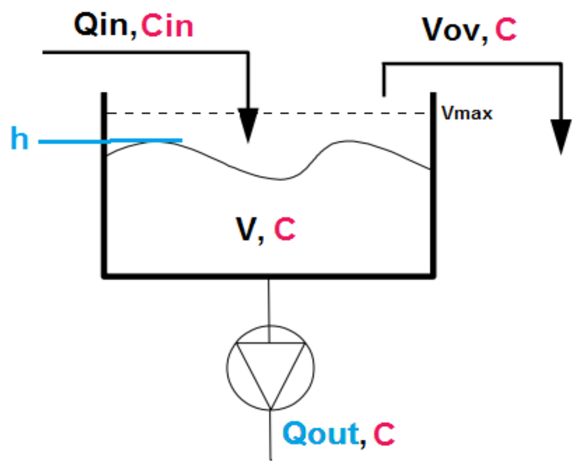
V: wastewater volume in the tank
Qout: outflow (measured and subject to control)
C: concentration of the pollutant load in the tank

Method: Wastewater Quality model

Three main assumptions, there is:

1. Only one global indicator to reflect the pollution load;
2. Only a simple dilution effect in the tank;
3. Homogeneous concentration of the pollutant load in the tank ‘C’

Taking into account previous equations and mass balance law:



System variables

$$m(t) = m(t-\Delta t) + m_{in}(t) - m_{out}(t) - m_{ov}(t)$$

$$C(t)V(t) = C(t-\Delta t)V(t-\Delta t) + C_{in}(t)Q_{in}(t)\Delta t - C(t-\Delta t)Q_{out}(t)\Delta t - C(t-\Delta t)V_{ov}(t)$$

$$C(t) = \frac{C(t-\Delta t)V(t-\Delta t) + C_{in}(t)Q_{in}(t)\Delta t - C(t-\Delta t)Q_{out}(t)\Delta t - C(t-\Delta t)V_{ov}(t)}{V(t-\Delta t) + [Q_{in}(t) - Q_{out}(t)]\Delta t - V_{ov}(t)}$$

Method: Optimization

Quantitative Objective Function

$$J = \sum_{n-t}^{t+H_P} \lambda\phi_1(n) + \beta\phi_2(n) + \alpha\phi_3(n)$$

Φ1: To use the storage capacity of the network homogenously.

$$\phi_1(n) = \sum_{i=1}^{N} \left(V_i(n) - \frac{V_{i_{max}}}{\sum_{j=1}^{N} V_{j_{max}}} \sum_{k=1}^{N} V_k(n) \right)^2$$

Φ2: To keep the flow towards the WWTP as close as possible to the optimum operating reference value.

$$\phi_2(n) = \left(y_{ref}(n) - \sum_{i \in N_k^*} Out_i(n - d_{i,k}) \right)^2$$

Φ3: To minimize the CSO volume.

$$\phi_3(n) = \sum_{i=1}^{N} (Ov_i(n) - NL)^2$$

$j = 1 \ldots N_P$: number of pipes in the network
$d_{i,k}$: the transport time of the i^{th} tank to the destination tank j (j = k representing the arrival at the treatment plant).
N^*_j : all the tanks draining directly to the destination j.
NL : a negative number to have a linear objective funciton

Method: Optimization

Qualitative Objective Function

$$J = \sum_{n-t}^{t+H_p} \lambda\phi_1(n) + \beta\phi_2(n) + \alpha\phi_3(n) + \gamma\phi_4(n) + \mu\phi_5(n) + \sigma\phi_6(n) + \left(\frac{\delta}{\phi_7(n)}\right)$$

Objectives:

Φ_4 : to minimize the overflowed mass.

Φ5 : to minimize the uncertainty present in the concentration of the mass which is directly linked to the above mentioned goal Φ_4.

Φ_6 : to distribute the pollutant mass over the network homogenously which is in fact similar to Φ_1.

Φ_7 : to maximize the pollutant mass arriving at the WWTP

$$\phi_4(n) = \sum_{i=1}^{N} (C_i(n)Ov_i(n) - NL)^2$$

$$\phi_5(n) = \sum_{i=1}^{N} (U_i(n) - NL)^2$$

$$\phi_6(n) = \sum_{i=1}^{N} \left(C_i(n)V_i(n) - \frac{V_{i_{max}}}{\sum_{j=1}^{N} V_{j_{max}}} \sum_{k=1}^{N} C_k(n)V_k(n) \right)^2$$

$$\phi_7(n) = \left(\sum_{i \in N_k^*} C_i(n - d_{i,k})Out_i(n - d_{i,k}) \right)^2$$

Constraints

The volume of wastewater in each tank, the outflow, and the wastewater contained in the pipes are all positive variables and limited by their maximum capacity

γ, μ, σ, and δ : the new weighting constants

Method: Uncertainty propagation

Taylor series of first order approximation

- **Reasons:**

1. because the qualitative model, although not linear, is differentiable.
2. Besides, through measures in the real system for each variable in our simple model there is an idea about the tolerance interval in which it is located.

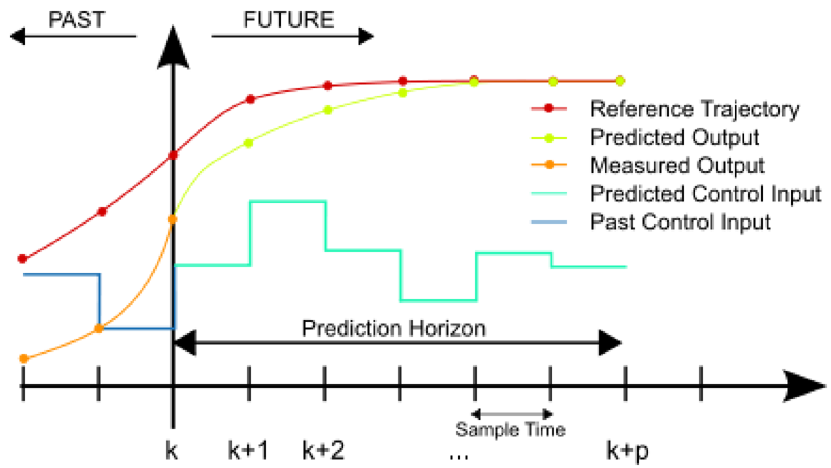
$$Var(C(t)) = U^2_{C(t)} = \sum_{i=1}^{6} \left(\frac{C(t)}{A_i}\right)^2 U^2_{A_i}$$

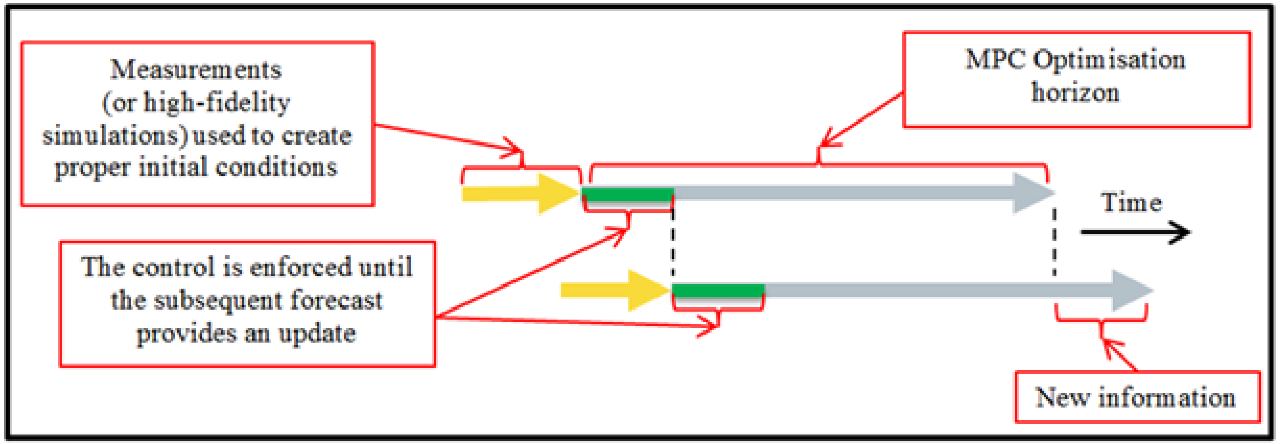
With:
$A_1 = C(t\text{-}\Delta t)$, $A_2 = V(t\text{-}\Delta t)$, $A_3 = Q_{in}(t)$, $A_4 = C_{in}(t\text{-}\Delta t)$, $A_5 = Q_{out}(t)$, $A_6 = V_{ov}(t\text{-}\Delta t)$.

$$U^2_{C_{in}(t)} = U^2_{C_{DW}(t)} \left(\frac{Q_{DW}(t)}{Q_{in}(t)}\right)^2 + U^2_{C_{WW}(t)} \left(\frac{Q_{WW}(t)}{Q_{in}(t)}\right)^2$$

Model Predictive Control (MPC)

An advanced real-time control (RTC) approach which employs an internal model in order to forecast the behaviour of the given system in future over a finite time horizon (receding horizon). The principle of receding horizon in shown here:



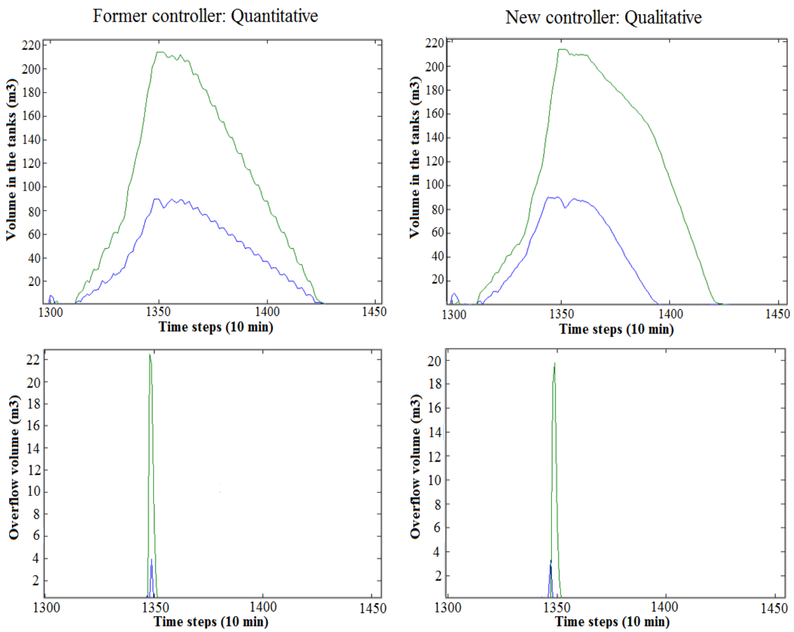


Results and Discussion

A) Comparison of the controllers quantitatively:

Volume in the tanks (m3) ⇨

Overflow volume (m3) ⇨



blue: Buderscheid CSO tank; green: Kaundorf CSO tank

Former controller: Quantitative	New controller: Qualitative
Overflow volume (Green): 52.8 m^3 Overflow volume (Blue): 4.5 m^3 Total overflow volume: 57.3 m^3	Overflow volume (Green): 45.9 m^3 Overflow volume (Blue): 3.5 m^3 Total overflow volume: 49.4 m^3

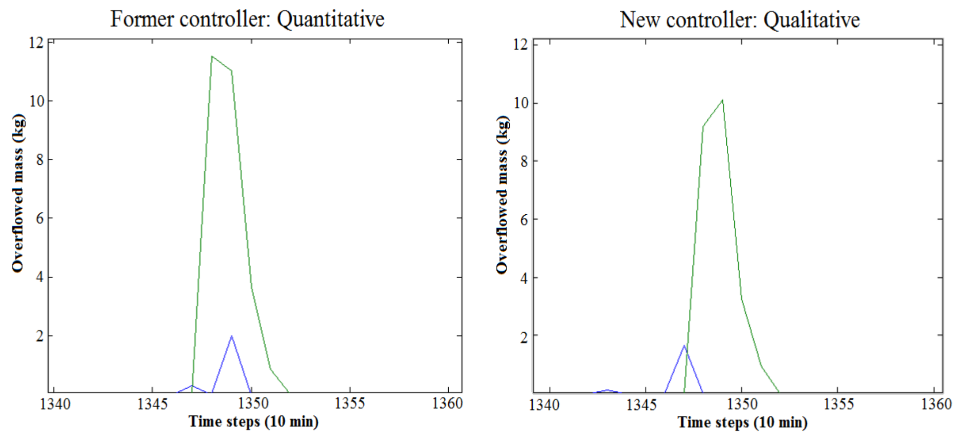
13.8% ↓

Results and Discussion

B) Comparison of the controllers

qualitatively:

Overflowed mass (kg)



blue: Buderscheid CSO tank; green: Kaundorf CSO tank

Former controller: Quantitative	New controller: Qualitative
Overflowed mass (Green): 27 kg Overflowed mass (Blue): 2.3 kg Total overflowed mass: 29.3 kg	Overflowed mass (Green): 23.5 kg Overflowed mass (Blue): 1.8 kg Total overflowed mass: 25.3 kg

13.6% ↓

The difference goes to the WWTP

Conclusions

- The main idea was to understand if the quality-based controller can **improve** the **performance** of the quantity-based controller.
- the results showed a positive contribution of the quality-based controller in **decreasing the overflowed pollution mass as well as CSO volume** during the selected rain scenario.
- the new controller reduces the pollution load and overflow volume **without** the need to add **new physical elements** (e.g. sensors) to the system which are normally expensive to purchase and maintain.
- In fact, this is a very promising result and can be considered as a **'soft' solution** for combined sewer network management.

Thank you for your attention

Any questions?

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Witteveen + Bos

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CTGA Centro Tecnológico de Gestão Ambiental

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eawag aquatic research

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