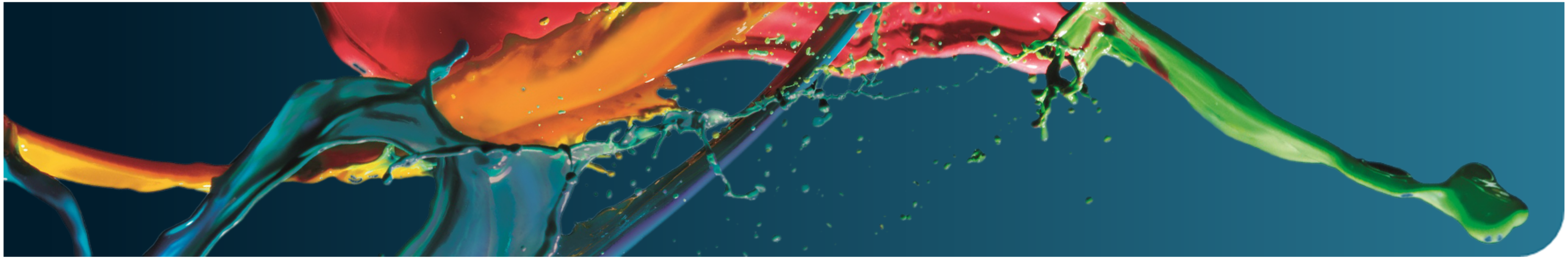
Optimization methods for hydraulic systems

September 13th, 2019, Jorn Baayen, Tjerk Vreeken, & Pierre Archambeau

Hydraulic optimization



Hydraulic optimization

The movement of water is governed by the Saint-Venant equations, which state that …

$$\Delta H \propto Q^2$$

This is nonlinear.

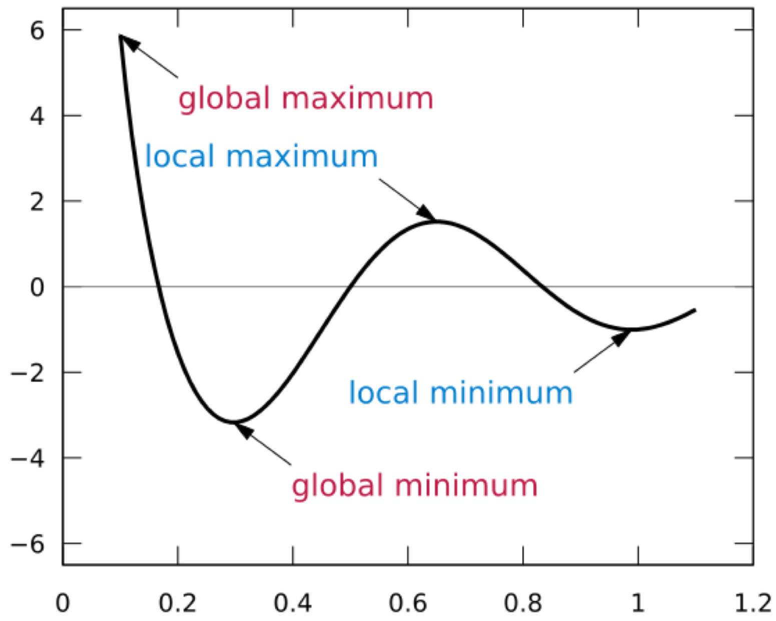
Furthermore, the wave propagation is dominated by both flow velocity $u = Q/A$ and water depth $\eta = \mathrm{H} - H_b$, i.e., $u \pm \sqrt{g\eta}$.

Hydraulic optimization

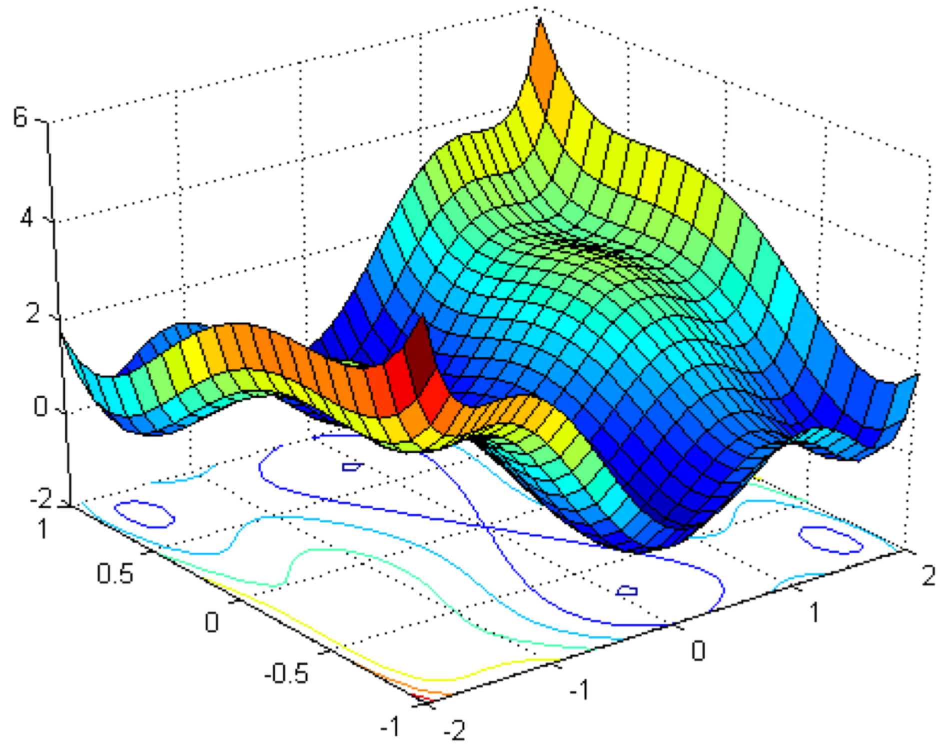
Optimizing nonlinear systems, such as those governed by

$$\Delta H \propto Q^2$$

is (in general) *very hard*:



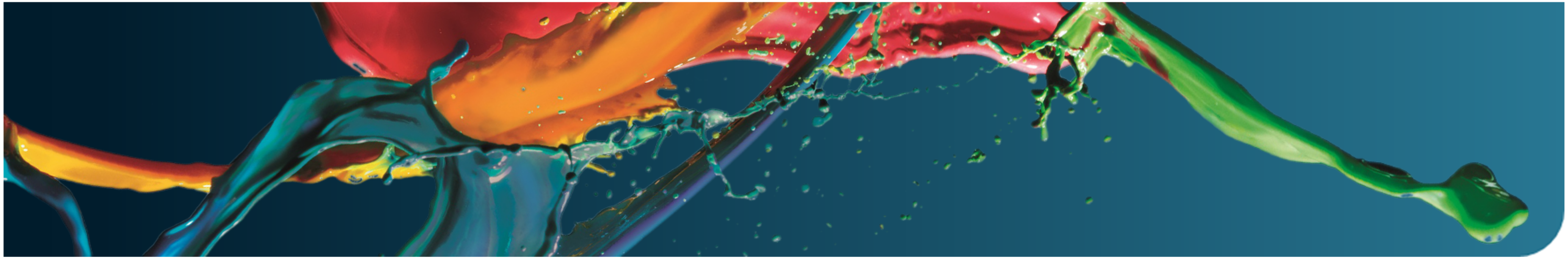
Hydraulic optimization



Imagine this in 45 weirs times 24 hours is 1080 dimensions …

… a *lot* of local minima.

Solution I: Genetic Algorithms



Reduced Genetic Algorithms

Idea behind the RGA

The RGA

- Uses a metaheuristic approach and a limited number of gate operation moments, with fixed time intervals (larger than the control step)
- Replaces standard GA operators (crossover and mutation) by a new methodology (diversification and intensification)

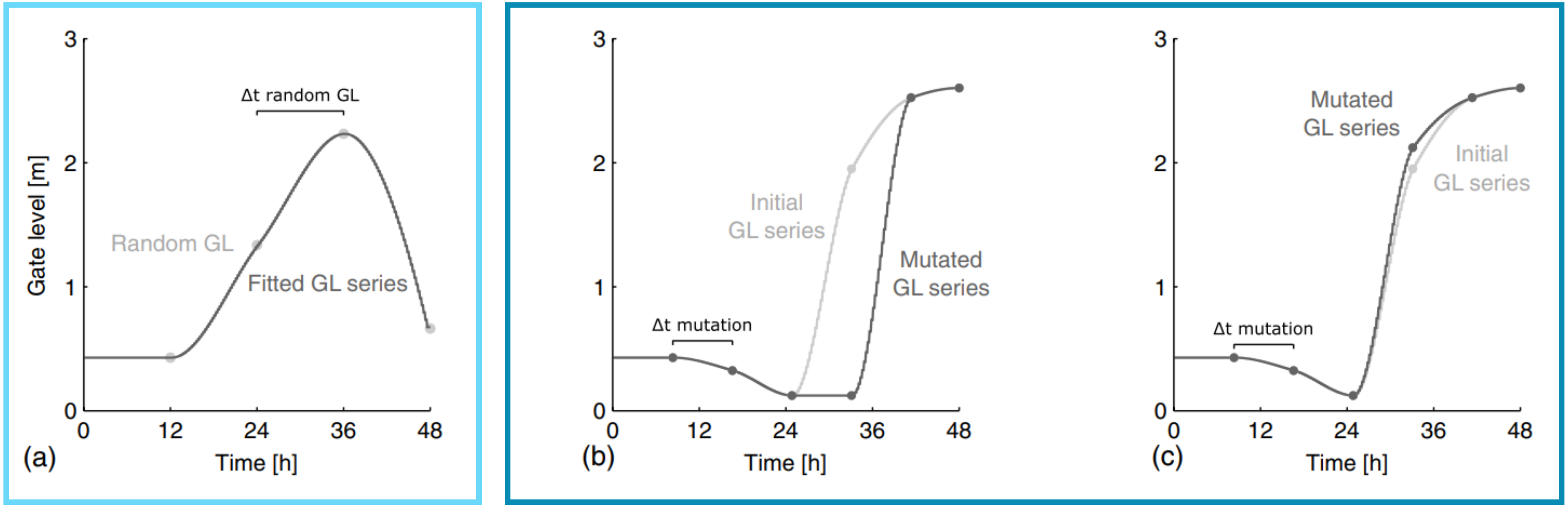
Details in Vermuyten, Meert, Wolfs, & Willems, *Combining Model Predictive Control with a Reduced Genetic Algorithm for Real-Time Flood Control,* 2018.

The RGA is **easy to code** and can be applied to all type of models (conceptual or physically based). Stopping criterion must be defined but usually a maximum number of scenarios is considered.

Reduced Genetic Algorithms

RGA operators

Creation | Mutation



Creating **new random** series | Mutating series by **diversification** or **intensification**

source : Vermuyten and al, J. Water Resour. Plann. Manage (2018)

Reduced Genetic Algorithms

Parameterization used for the benchmarks

Number of random/mutation **10000/2000** independently of the number of level nodes

Random frequency **8** h

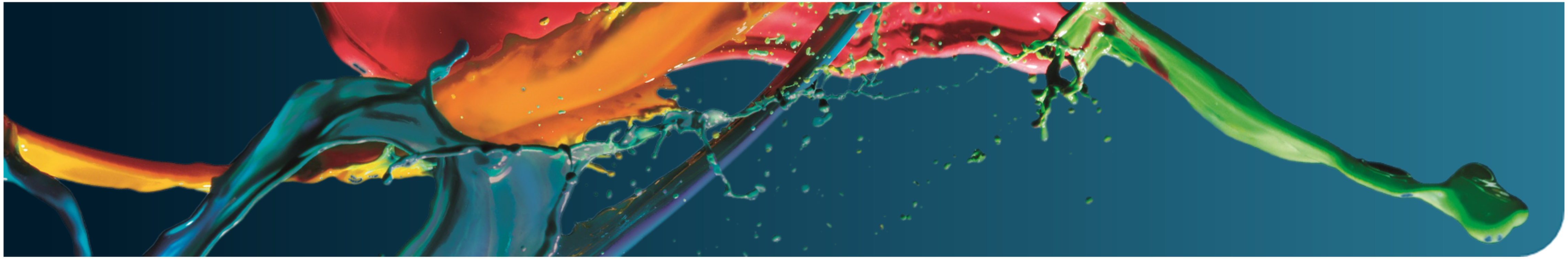
Mutation frequency = Control time step (minimum 1h ; maximum 8h)

Probability diversification/intensification **0.5**

Weirs

- Lower Limit **0** m^3/s
- Upper Limit **200** m^3/s
- Sensitive range **20**%

Solution II: Globalized Interior Point Method (the “GIP”)



Globalized Interior Point Method

The idea

The GIP

- Uses mathematical topology (homotopy) to transfer global optimality of simplified problem to complete nonlinear problem.
- Finds solutions by applying Newton's method to find zeroes of the Lagrangian (the *second order method* underlying industry standard packages such as **IBM CPLEX** and **MOSEK**).
- Produces a **certificate** that the solution is **globally optimal**.

Details in Baayen, Piovesan, and VanderWees, *Continuation method for PDE-constrained global optimization: Analysis and application to the shallow water equations*, 2019.

Outlook

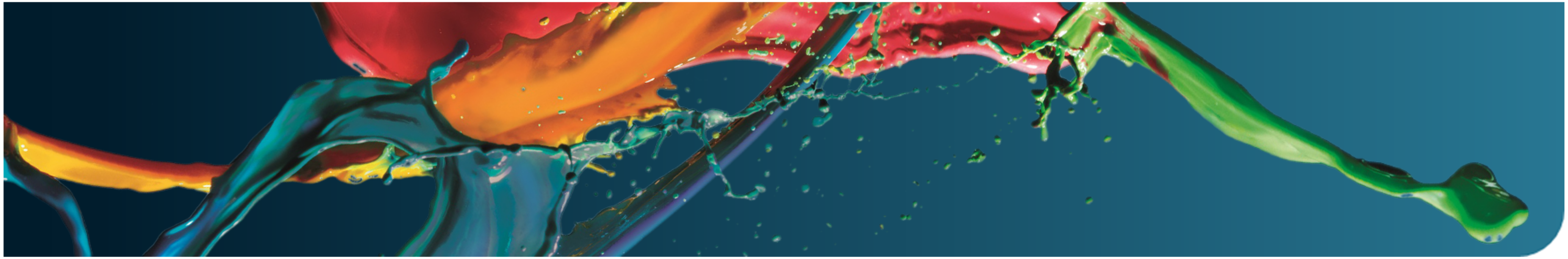
Outlook for the GIP

KISTERS Real Time Optimization (RTO) is the first and so far only software implementation of the GIP. It can load existing SOBEK or HEC-RAS models and set up correctly formulated optimization problems automatically.

Collaboration is ongoing between IBM and KISTERS to integrate GIP and CPLEX technology.

KISTERS RTO powered by CPLEX will bring IBM's three decades of *mixed integer* solver expertise to the technology stack.

Comparison



Benchmark setting

Model

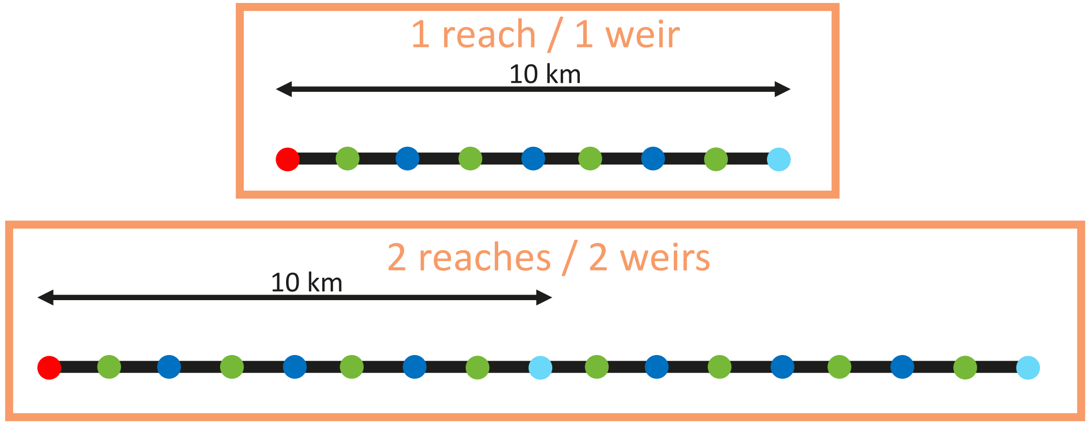
Mathematical hydraulic model	1D full Saint-venant
Numerical model	
spatial scheme	Staggered grid finite difference
temporal scheme	Euler semi-implicit
friction law	Chezy
upstream BC	Prescribed hydrograph ; 100 → 300 [m³/s]
downstream BC	Optimized hydrograph ; adjustable weir with upper limit 200 [m³/s]
Dimensions of one reach	
cross section	Rectangular with width = 50 [m]
length	10 [km]
slope	2 [m/km]

Benchmark setting

Parameters for 48 hours optimization horizon

Total computation points (level nodes)	[16; 32; 64; 128; 256; 512]
Hydraulic time step	[5 min; 10 min; 15 min]
Control time step	[1 hour; 2 hours; 4 hours; 8 hours]
Adjustable weirs	[1; 2; 4; 8; 16] spaced every 10 km

… total of **360** combinations



- level (green)
- upstream discharge (red)
- optimized discharge (light blue)
- internal discharge (blue)

Benchmark setting

Optimization objective

Tracking problem: The optimization objective is to steer the water levels just upstream and downstream of a reach to the reference value.

Both optimization algorithms were seeded with constant 100 m^3/s weir flow hydrographs.

The benchmarks were run (repeatedly - min 10x) on an Amazon Web Services "c x4large" node:

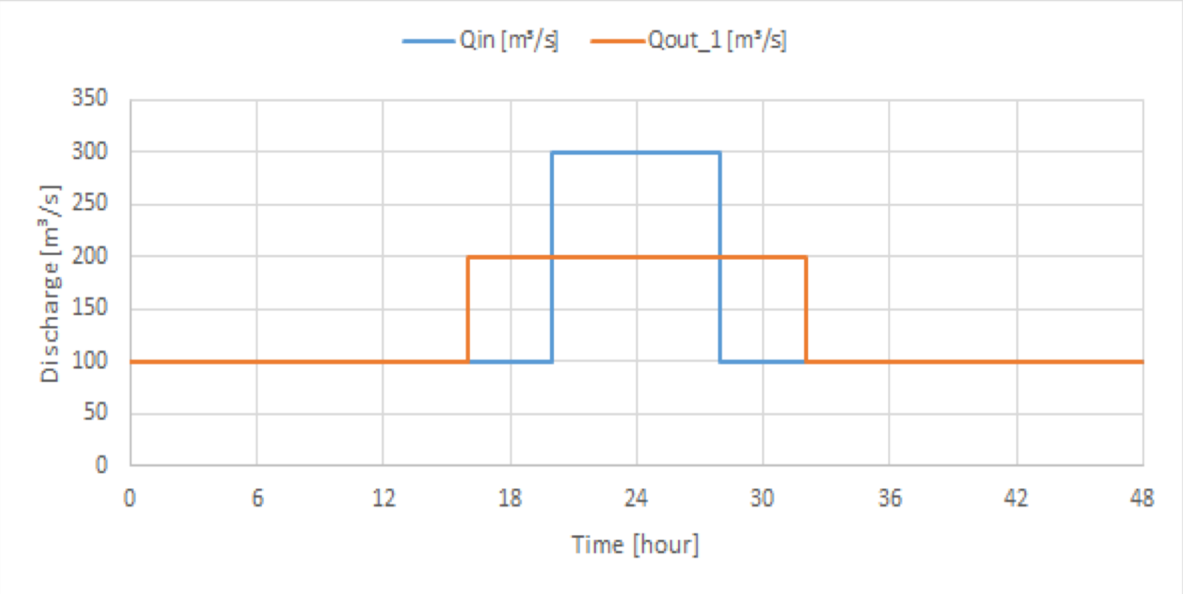
- 16 Intel Xeon processors @ 3.0 GHz.
- 32 GB RAM.
- Ubuntu Linux 18.04.3 LTS.

Benchmark results

Illustration of results for a single level lode per reach

In the specific case ***n*** level nodes and ***n*** weirs:

- Only one level node exists per reach
- The constraints are linear (mass balance)
- The objective function is quadratic

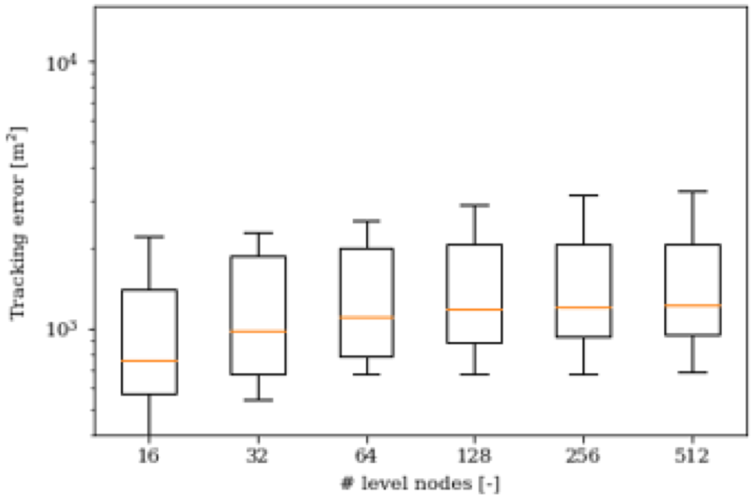


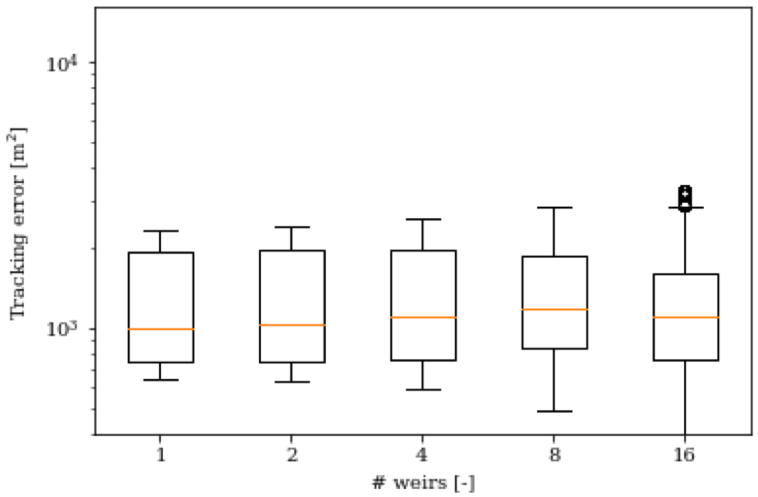
The problem admits an obvious optimal solution

- The input signal is damped by the first reach
- All weirs work at full capacity (200 m³/s) for twice as long as the input signal
- The output hydrograph is then repeated indefinitely without damping

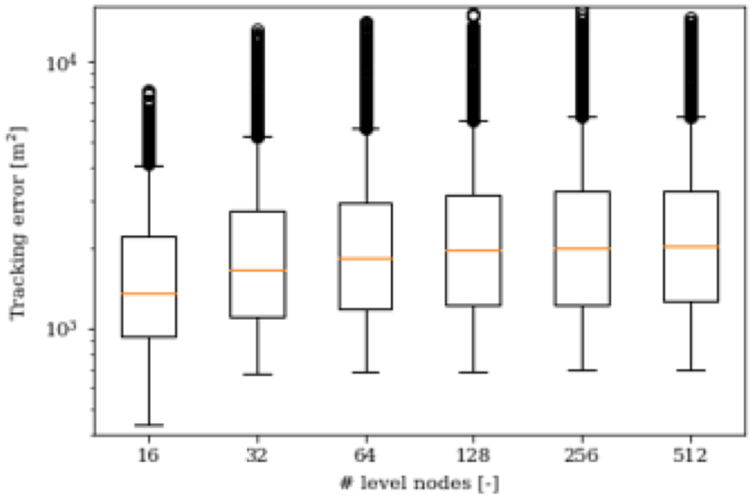
Benchmark results – Tracking error

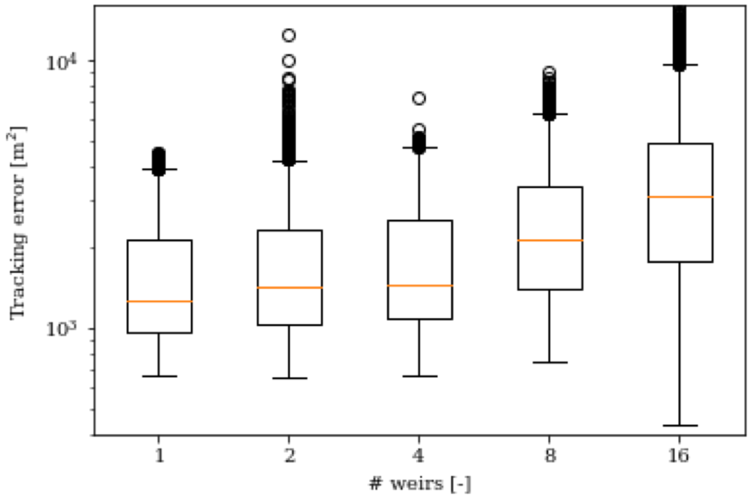
RTO





RGA





Benchmark results – Tracking error

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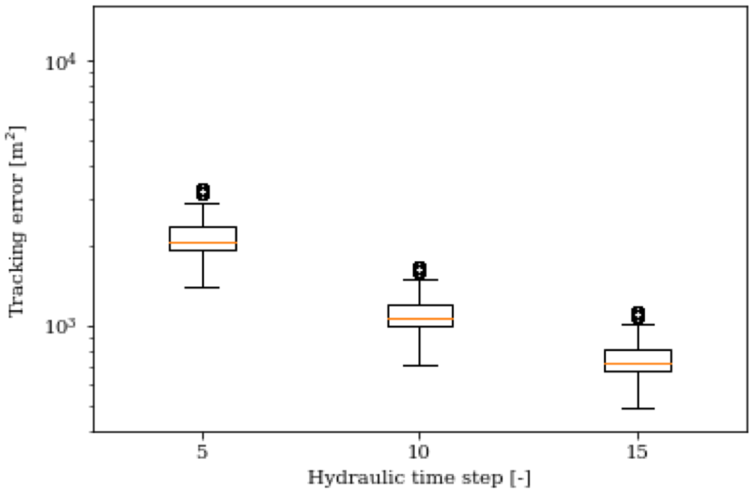
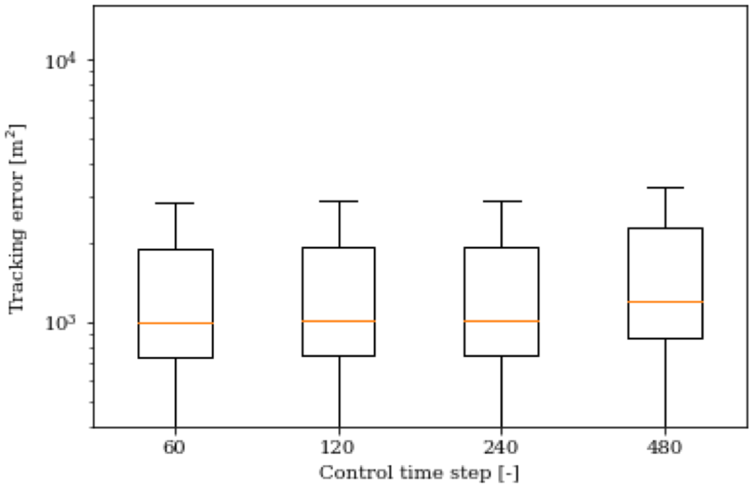
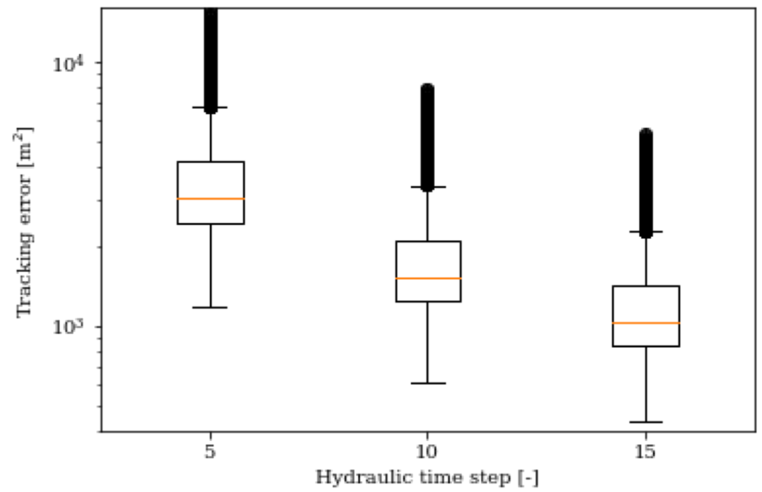
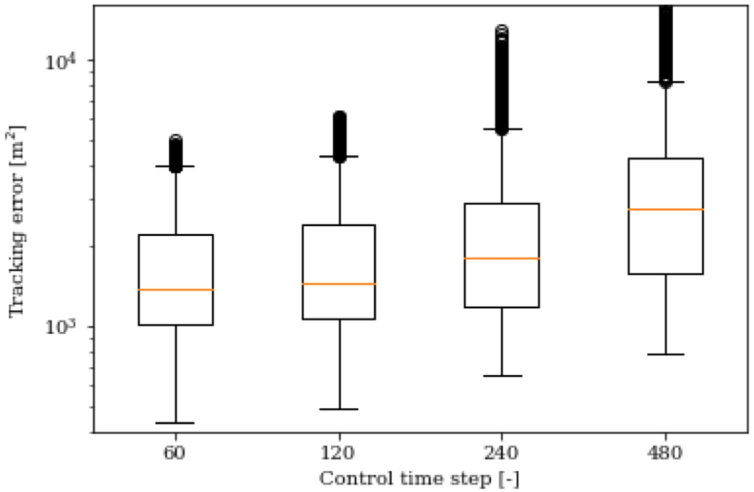
RTO





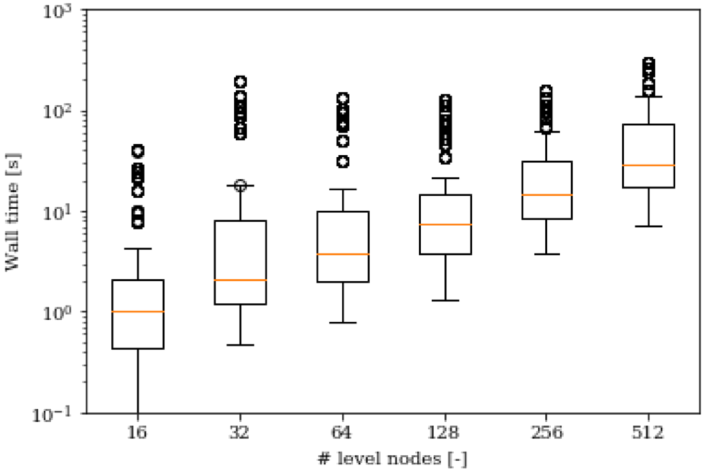
RGA

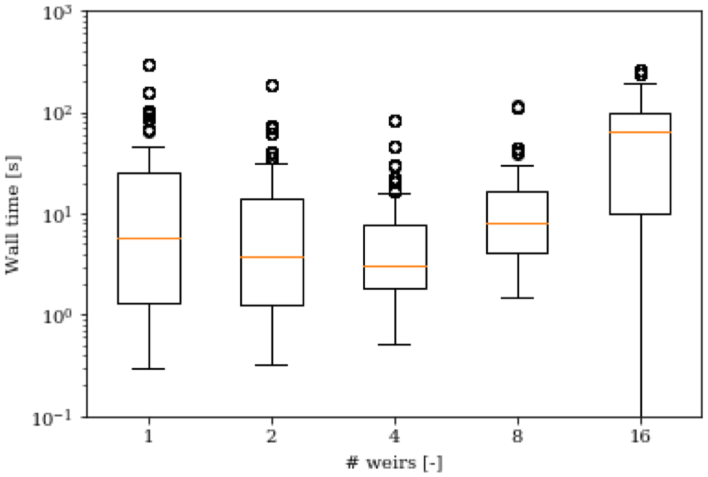




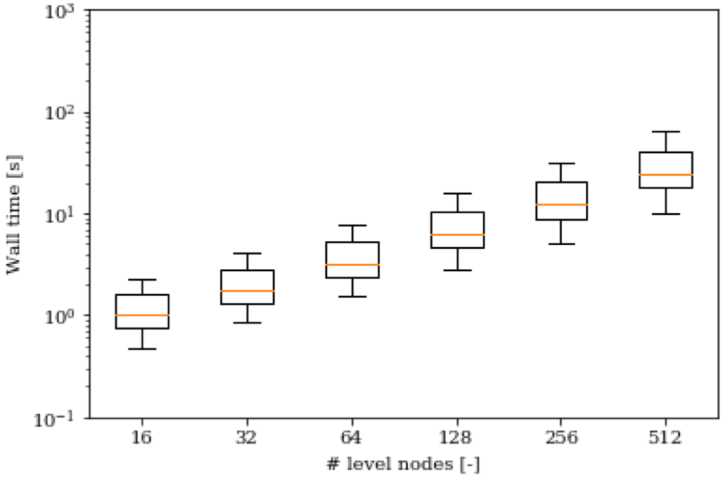
Benchmark results – Wall time

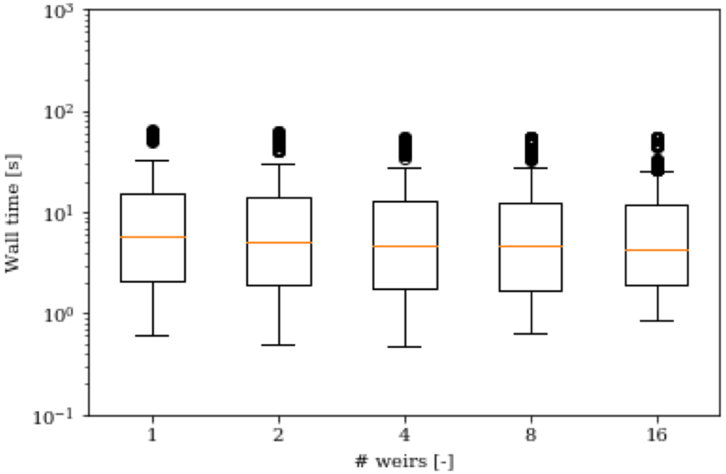
RTO





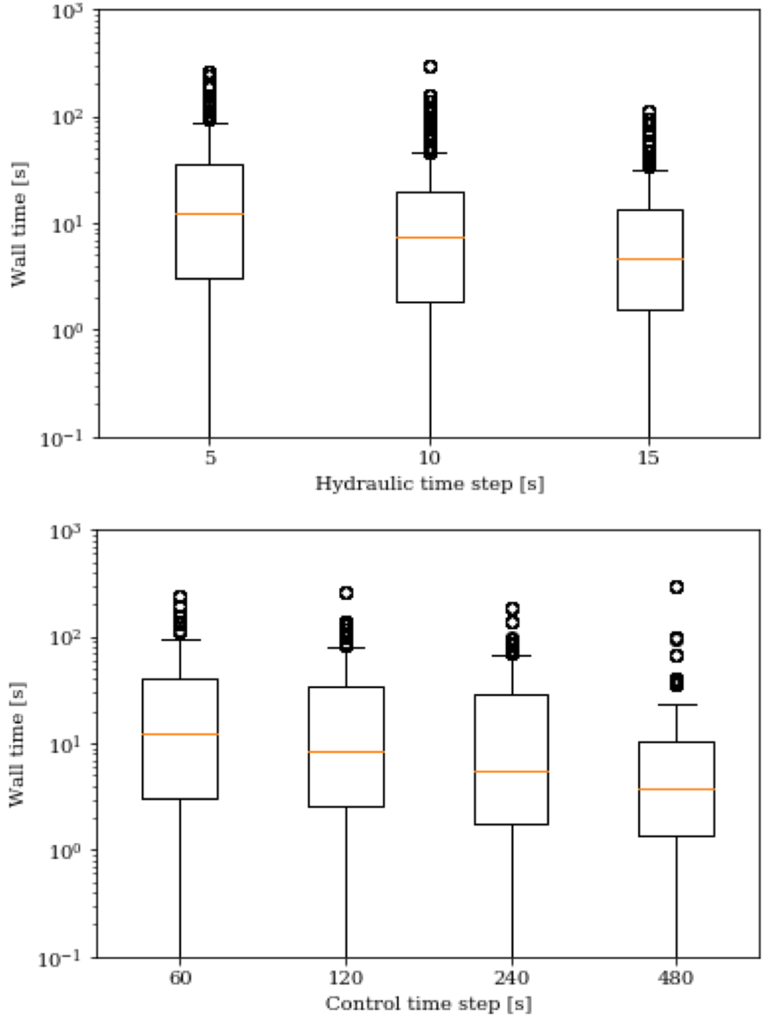
RGA



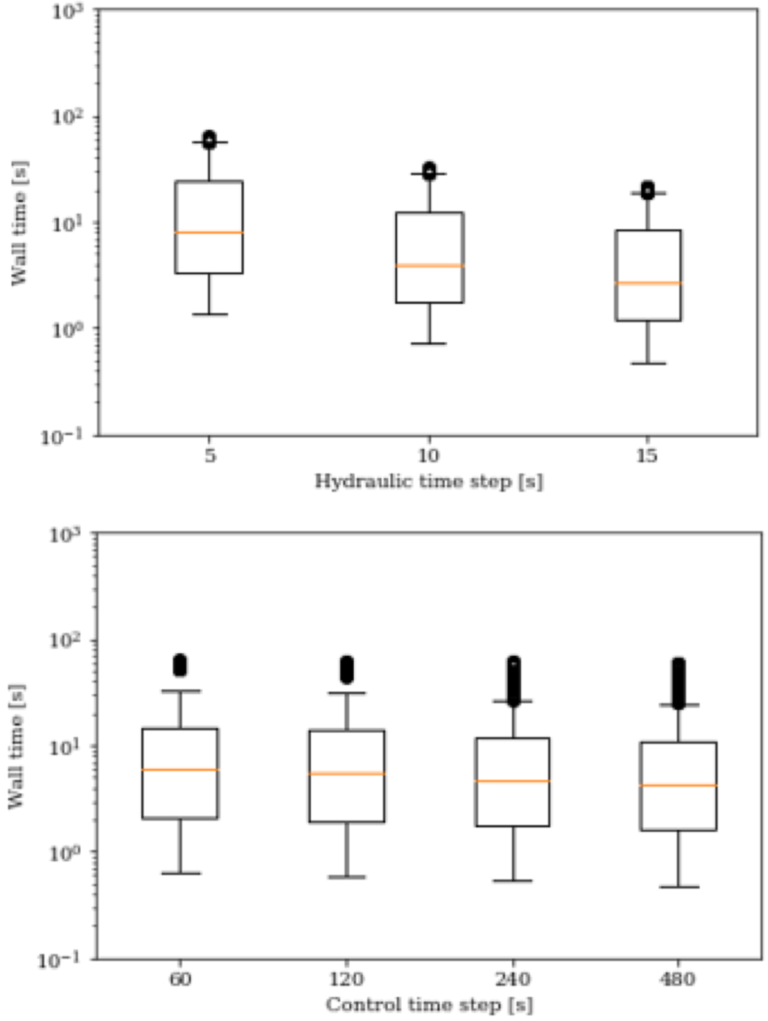


Benchmark results – Wall time

RTO

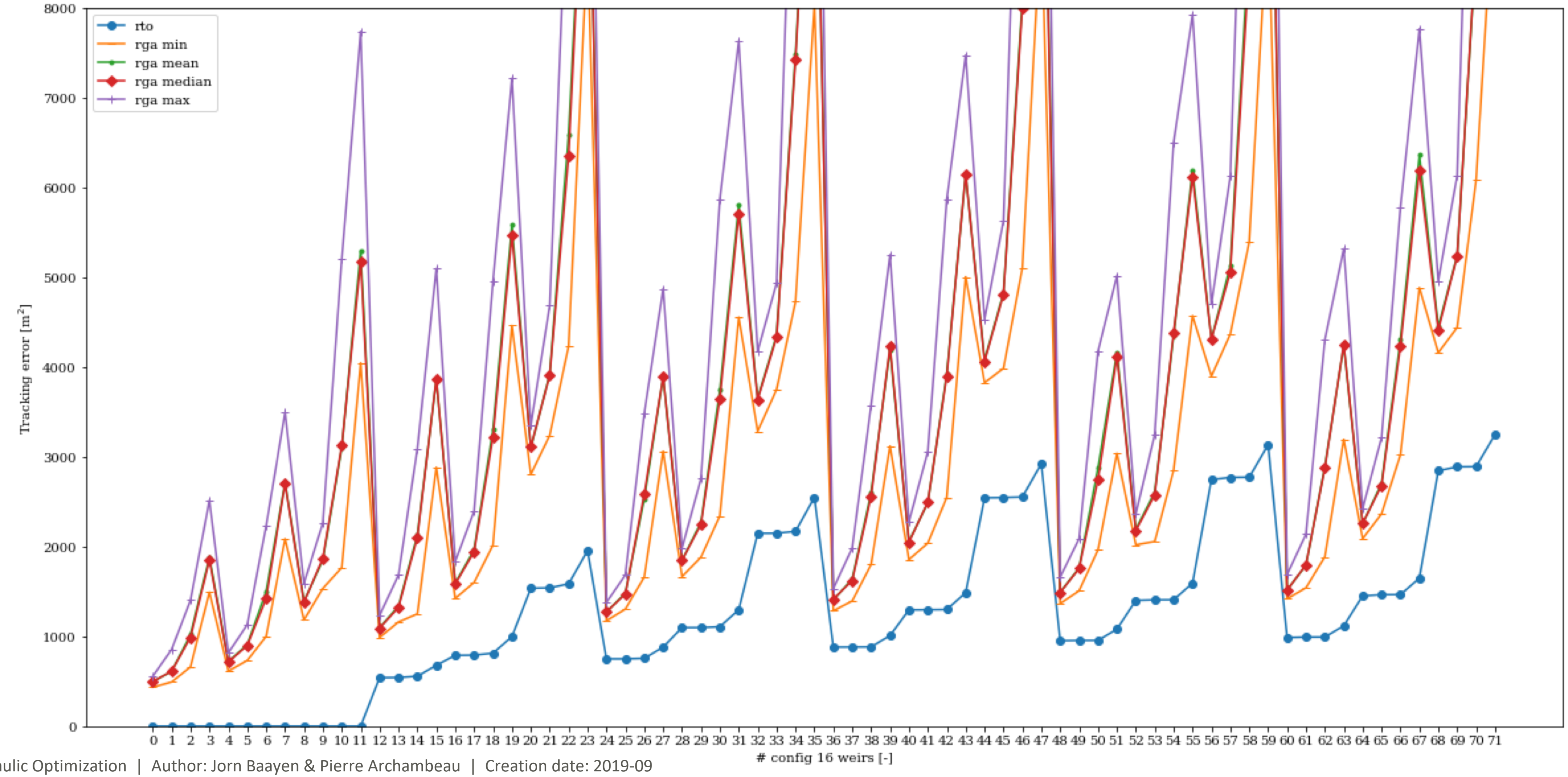


RGA



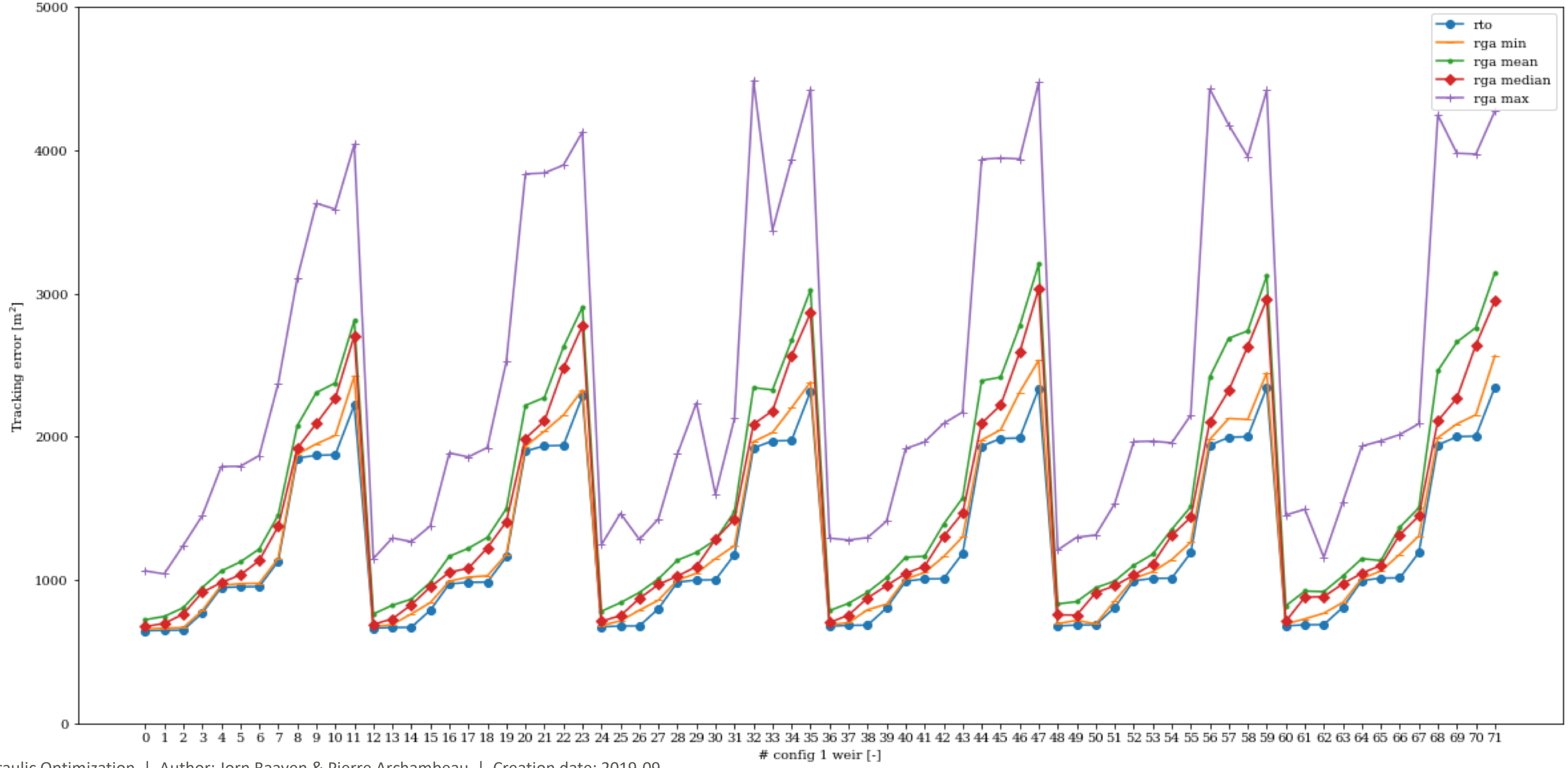
Benchmark results

72 combinations for 16 weirs – sorted by (nb level nodes ; hydraulic dt ; control time step)



Benchmark results

72 combinations for 1 weir – sorted by (nb level nodes ; hydraulic dt ; control time step)



Conclusions

The results show a clear complementarity. The continuation method produces significantly better solutions, but requires more computation time than the reduced genetic algorithm.

	Reduced genetic algorithm	Continuation method
Solution optimality	Suboptimal	Globally optimal
Solution determinism	Non-deterministic	Deterministic
Computation time	Low	Moderate

Notes:

- The problem formulation used for the benchmark has a single, global optimum. The RGA solutions are therefore nor global, nor local minima.

- The source code of our RGA implementation is available for review.

- Access to the KISTERS Real Time Optimization REST API may be requested for purposes of independent result verification.

Recommendations

Our results lead to the recommendation that:

- GIP be used for mission-critical applications, such as real-time flood control:

  Who would trade CPU time for flood damage?

- GIP be used for hydropower optimization:

  In our world, every megawatt of renewable energy is needed.

- RGA be used for exploratory desk studies, where user interaction and fast results are needed.

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