PhD Course
Modelling Of Integrated Urban Drainage-Wastewater Systems

DTU Environment - Department of Environmental Engineering

A practical protocol for calibration of nutrient removal wastewater treatment models

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Université Laval

bc3 Basque Centre for Climate Change
Klima Aldaketa Ikergai

Background

Needs to protect surface water bodies against eutrophication phenomena

Optimization of nutrients removal processes in WWTPs

New technologies to achieve more stringent limits for total nitrogen and total phosphorus

Modelling tools to predict, control and assess nitrogen and phosphorus biological removal processes

MATHEMATICAL MODELS
as a common key point

- ✓ To test hypotheses on functional interactions in the system
- ✓ As compact and transparent archives of knowledge
- ✓ To predict future states of the system

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Background

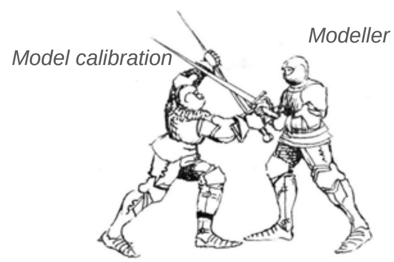
Activated Sludge Models (ASMs) (Henze et al., 2000) are largely used in WWTPs

Complex environmental models

- Several parameters to be assessed
- Several model outputs to be fitted with measured data
- Limited quality data are available

➔ Over-parameterized models

➔ Model Calibration is a very challenging task



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Calibration of ASMs

Introduction

Different systematic calibration protocols have been proposed in recent years: the STOWA protocol (Hulsbeek et al., 2002), the BIOMATH calibration protocol (Vanrolleghem et al., 2003), the WERF protocol (Melcer et al., 2003) and HSG guidelines (Langergraber et al., 2004) whose objective is to aid modeler during calibration study.

Insel et al. (2006) proposed a step-wise methodology to calibrate nutrient removing SBRs models based on four iterative steps sequentially calibrating NH_4-N, O_2, NO_3-N and PO_4-P; this methodology was included into the BIOMATH by Corominas et al. (2008).

Protocols and methodologies have attempted to tackle the rather complex calibration issue of ASMs, but still remains one of the main bottleneck/time demanding tasks in modelling study (Hauduc et al., 2009).

A standard approach in performing a calibration study for WWTP model is lacking and still holds!

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Proposed protocol

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A practical protocol for calibration of nutrient removal wastewater treatment models

Giorgio Mannina, Alida Cosenza, Peter A. Vanrolleghem and Gaspare Viviani

ABSTRACT

Activated sludge models can be very useful for designing and managing wastewater treatment plants (WWTPs). However, as with every model, they need to be calibrated for correct and reliable application. Activated sludge model calibration is still a crucial point that needs appropriate

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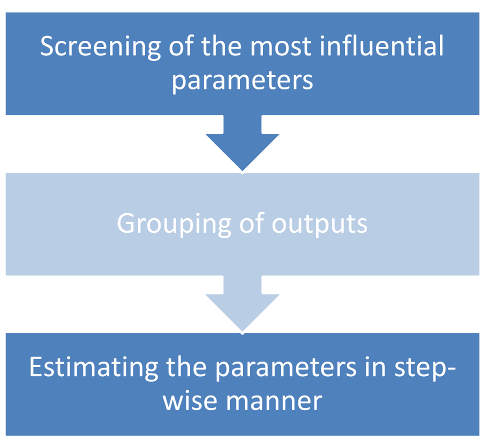
Proposed protocol

The Idea

Step-wise procedure for simultaneous parameter estimation and sensitivity analysis using Monte Carlo simulation



Mannina et al., 2011

Proposed protocol *Description*

The step-wise procedure is divided into two phases.

Parameter subsets selection

Six sub-steps

Model Calibration (iterative steps)

Four sub-steps

Mannina et al., 2011

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Proposed protocol *Phase 1: Parameter subset selection*

1. Define the set of representative model outputs
2. Define the set of *a priori model* parameter values
3. Define the variation range and distribution of each model parameter
4. Monte Carlo simulations with the variation of the single model parameter (local) or Global Analysis
5. Calculate the sensitivity coefficient $s_{i,j}$
6. Define the set of the influential parameters for each representative model output
   - *i. Define N groups of representative model outputs and their calibration order*
   - *ii. Select the sensitive parameter subset for each group*

Broadest from literature/ uniform in case no knowledge is available

In the local analysis likelihood measures have to be computed to quantify the influence of parameters on the model outputs

Scale si,j values, fix threshold, select influential parameter!

For example putting together all variable related to N, or P! Then establish calibration hierarchy

All parameters influential at least for one model outputs of the group

Mannina et al., 2011

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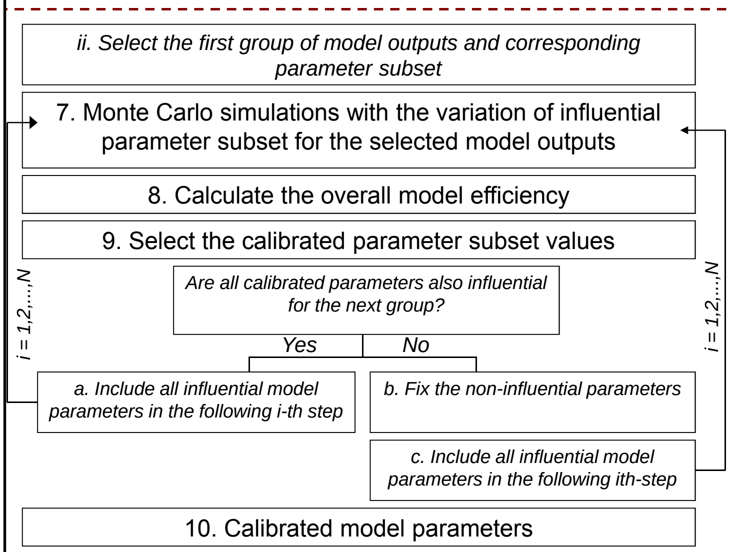
Proposed protocol

Phase 2: Model calibration



Generalized Likelihood Uncertainty Estimation methodology

As weighted sum of the likelihood measures of the n model outputs!

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Proposed protocol

Likelihood measure

$$L(\theta_i/Y_j) = \exp\left(\frac{-\sigma^2_{M_j-O_j}}{\sigma^2_{O_j}}\right)$$

Likelihood measure

where:
θ_i is the *i-th* set of model parameter (randomly generated),
$\sigma^2_{M_j-O_j}$ is the standard deviation between modelled and observed results of the *j-th* model output;
$\sigma^2_{O_j}$ is the standard deviation of the measured data related to the *j-th* model output

$$E_i = \sum_j^n \alpha_j L(\theta_i/Y_j)$$

Overall model efficiency

where:
α_j is the weight of the *j-th* model output

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Protocol applications

- ✓ **Example 1**: ASM2 model (modified) applied to a full scale WWTP (Mannina et al., 2011)
- ✓ **Example 2**: Integrated ASM2d-SMP-P model applied to an MBR pilot plant WWTP(Cosenza et al., 2013)

Protocol applications

Example 1

Protocol applications *Example 1: Model structure*

To improve model performance some processes and variables of ASM1 have been included

20 processes
- Hydrolysis processes (e.g. of X_{ND})
- Heterotrophic organisms processes: X_H
- Phosphorus accumulating organisms (PAO): X_{PAO}
- Nitrifying organisms (autotrophic organisms): X_{AUT}
- Ammonification

17 variables

<u>PARTICULATE</u>

X_I, X_S, X_H, X_{PAO}, X_{PP}, X_{AUT}, X_{PHA}, X_{ND}, X_{TSS}

<u>SOLUBLE</u>

S_{O2}, S_F, S_A, S_{NH4}, S_{NO3}, S_{PO4}, S_{ND}, S_I

41 parameters
- Fractionation
- Kinetics
- Stoichiometrics

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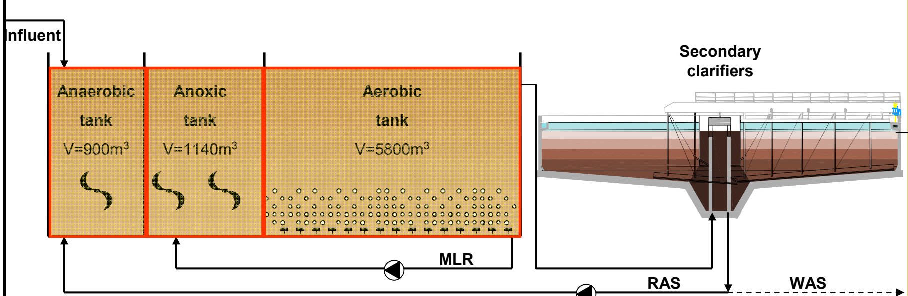
Protocol applications *Example 1: Case study*

The municipal activated sludge WWTP under study is located Sicily (Italy), with outflow in the Mediterranean Sea.
The plant treats both domestic and non-industrial wastewater produced by a nearby refinery (40,000 inhabitant equivalents).
The WWTP secondary treatment processes consists of an activated sludge reactor, according to a Bardenpho scheme, and a secondary clarifiers



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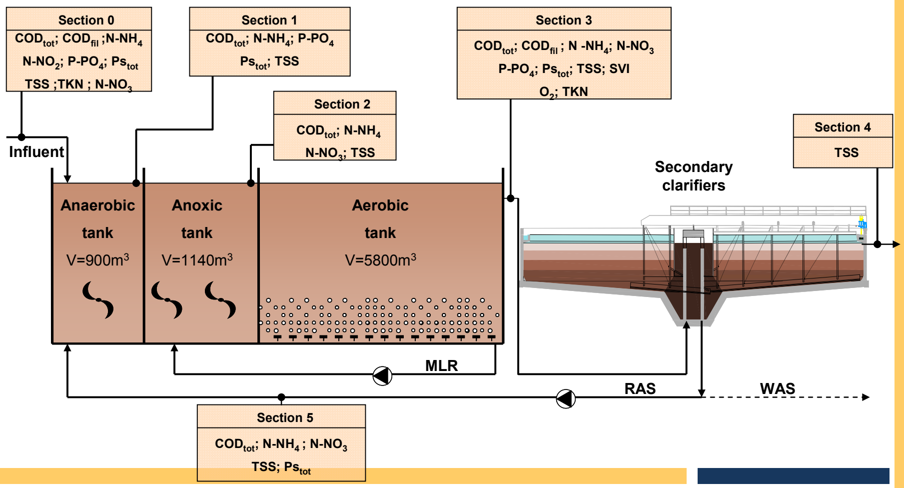
Protocol applications *Example 1: Measurements*

An extensive field data gathering campaign has been carried out during the period from 01 March 2006 to 12 April 2006 (3 days per week); 1-day hourly sampling campaign (section 0) was conduced to determine the pattern of influents pollutants

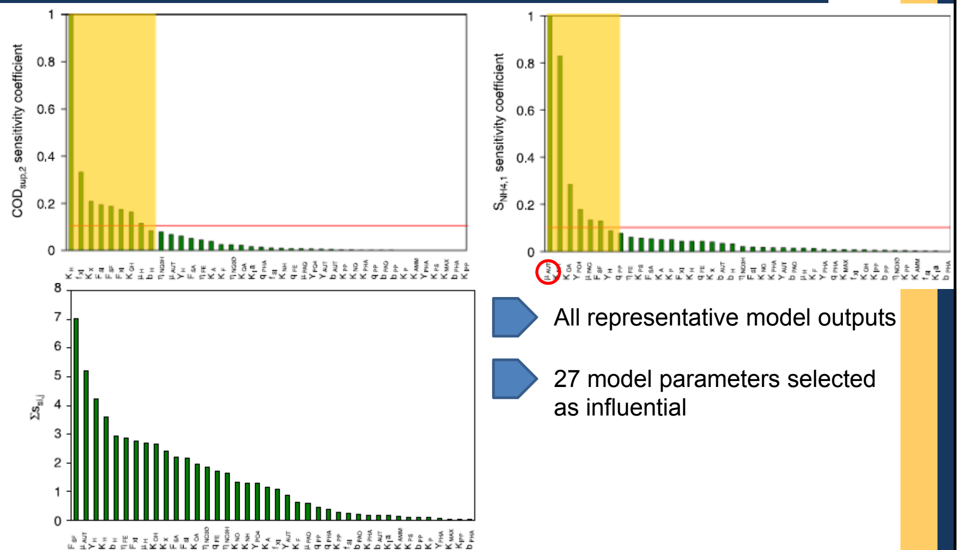


Protocol applications *Example 1: Numerical settings*

- ✓ 15 representative model outputs
- ✓ 4 group of model outputs: COD, TSS, N and P
- ✓ Local sensitivity analysis: 1,500 Monte Carlo simulations for each parameter
- ✓ Threshold for scaled sensitivity index = 0.1
- ✓ 10,000 Monte Carlo runs for each group of model outputs

Protocol applications

Example 1: Results phase 1



- All representative model outputs
- 27 model parameters selected as influential

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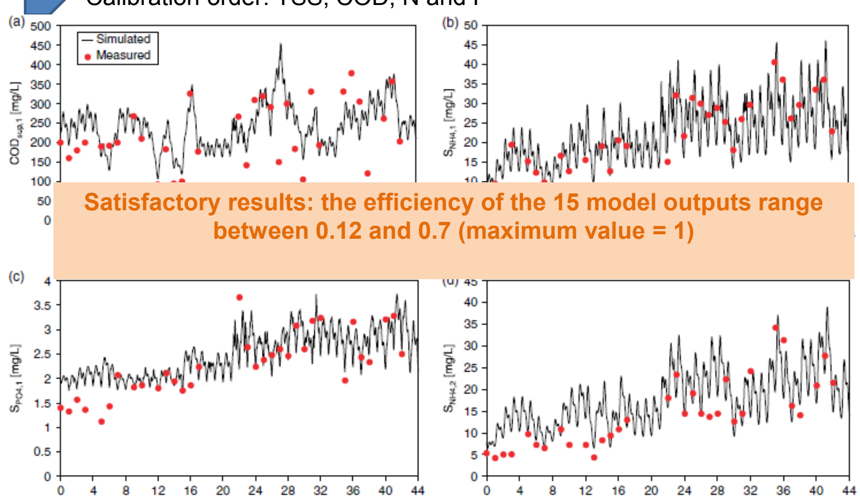
Protocol applications

Example 1: Results phase 2

- Calibration order: TSS, COD, N and P



Satisfactory results: the efficiency of the 15 model outputs range between 0.12 and 0.7 (maximum value = 1)

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Protocol applications

Example 2

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Protocol applications *Example 2: Model structure*

Integrated ASM2d-SMP-P model
(26 processes, 19 variables and 79 parameters)

Biological sub-model
(ASM2d-SMP introduced by Jiang et al., 2008)

- COD removal
- Nitrogen removal
- Phosphorus removal
- SMP formation/degradation

Physical sub-model
(introduced by Mannina et al., 2011)

- Superficial deposition (cake layer)
- Physical membrane filtration

Cosenza et al., 2013

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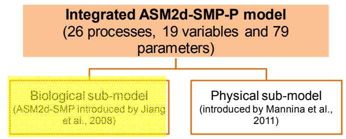
Protocol applications *Example 2: Model structure*



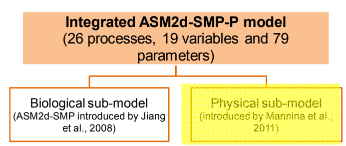
The biological sub-model is a modified version of ASM2d (Henze *et al.*, 2000) according to Jiang et al., 2008:

- Two new state variables S_{UAP} and S_{BAP} ($S_{UAP}+S_{BAP}=SMP$)
- 6 new processes (anaerobic, anoxic and aerobic hydrolysis of UAP and BAP)

The general assumptions of the sub-model are:

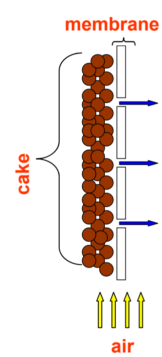
- SMP are defined to have a size <0.45μm
- Both BAP and UAP are produced in MBR system
- Both BAP and UAP are biodegradable

Protocol applications *Example 2: Model structure*



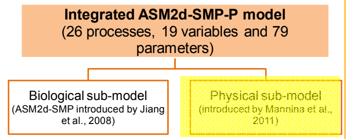
Physical sub-model hypothesis

- The membrane retains all particulate (X) components
- Cake formation during the process filtration as suggested by Li and Wang (2006)
- Partial retaining of soluble (S) components by cake layer and membrane according to *deep bed theory* (Bai and Tiene, 2000; Kuberkar and Davis, 2000)

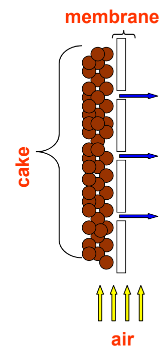


Protocol applications *Example 2: Model structure*

The physical model consists of 3 main processes



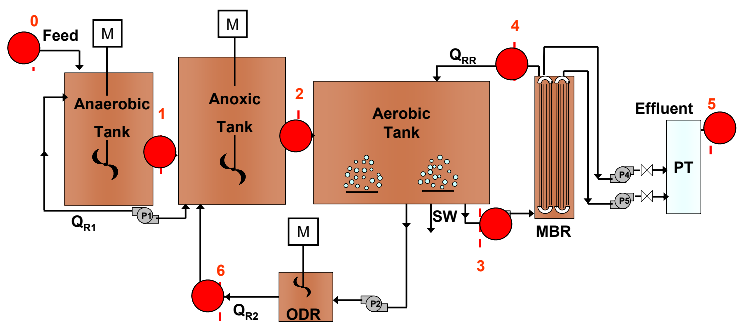
- Cake layer formation during the membrane filtration
- COD removal by biological membrane (cake layer) according to deep bed theory (Bai and Tien, 2000; Kuberkar and Davis, 2000)
- COD removal by physical membrane



Resistances of dynamic biofilm, stable cake and pore fouling are modelled by means of in-series resistance model

$$R_{tot,i}(t) = \underbrace{R_m + R_{p,i} + R_{sc,i}(t)}_{R_{irr}} + \underbrace{R_{dc,i}(t)}_{R_{rev}}$$

Protocol applications *Example 2: Case study*



- UCT-MBR pilot plant
- fed with 40 L/h of municipal wastewater
- **2 hollow fibre membrane modules** pore size of 0.04 μm Zenon Zeeweed- ZW 10
- **165** days **operation** - until day 76 complete sludge retantion, after day 76 **SRT** mintained **37 days**
- F/M 0.13 kgTCOD·kgVSS^{-1} d^{-1}
- Data **3 times** per week in all sections

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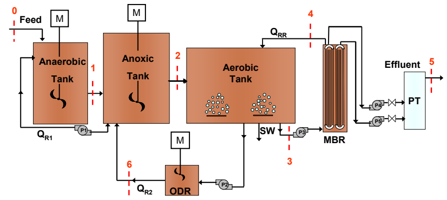
Protocol applications *Example 2: Case study*

- - - - Sampling point



Samples

- Composite influent wastewater (section 0)
- Grab mixed liquor in each tank sections(1- 4) in ODR (section 6) and permeate (section 5)

Analysed 3 times per week for:

TSS, VSS, COD_{TOT}, COD_{SOL}, NH_4-N, NO_2-N, NO_3-N, N_{TOT}, P_{TOT} (APHA, 1998).

daily measurements in each section were conducted for dissolved oxygen (DO), pH and temperature (T).

A physical-chemical characterization of the influent was performed analysing COD, NH_4-N, NO_2-N, NO_3-N, N_{TOT} and P_{TOT} from influent grab samples withdrawn at hourly intervals during 24 hours

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Protocol applications *Example 2: Numerical settings*

- ✓ 21 representative model outputs (in different sections of the pilot plant)
- ✓ 4 group of model outputs: COD, TSS, N and P
- ✓ Global sensitivity analysis- SRC method: a parameter matrix (800 × 79) was generated using Latin hypercube sampling (LHS) (no reference to the measured data!)
- ✓ Global sensitivity analysis has been performed on the time-averaged state variables
- ✓ abs(β_i) with values above 0.1 were selected as being influential
- ✓ 10,000 Monte Carlo runs during calibration

β_i, slope of multivariate linear regression between model outputs and parameters, indicates the influence of parameters

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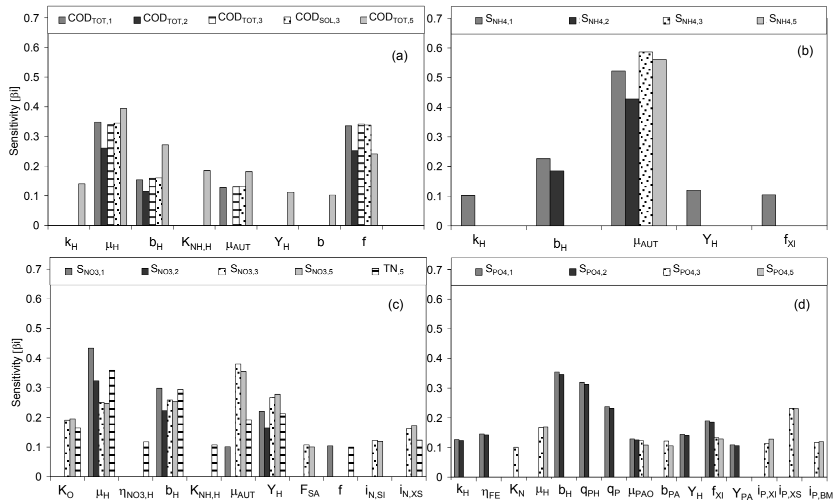
Protocol applications

Example 2: Results phase 1



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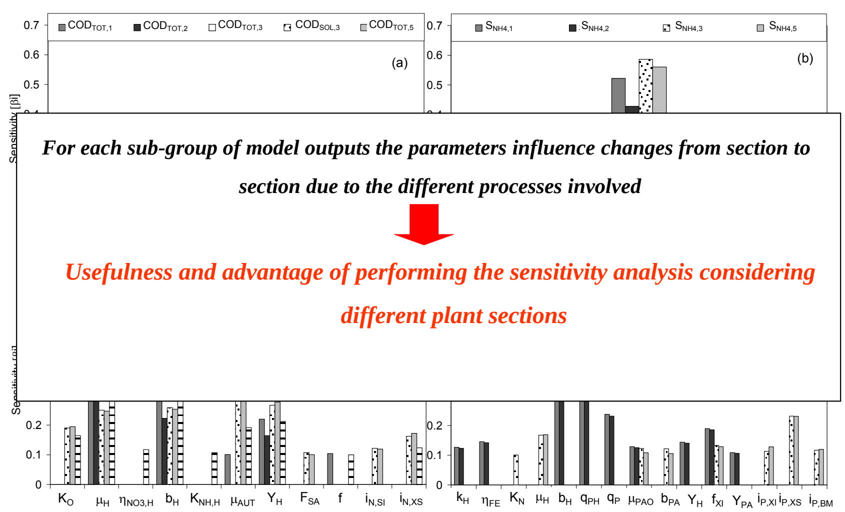
Example 2: Results phase 1



For each sub-group of model outputs the parameters influence changes from section to section due to the different processes involved

Usefulness and advantage of performing the sensitivity analysis considering different plant sections

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Protocol applications *Example 2: Results phase 1*

	Sub-group	Model output	Influential parameters sub-group
I	P	$S_{PO,1}$, $S_{PO,2}$, $S_{PO,3}$, $S_{PO,5}$	k_H, η_{FE}, K_{NO3}, μ_H, b_H, q_{PHA}, q_{PP}, μ_{PAO}, b_{PAO}, Y_H, f_{XI}, Y_{PAO}, $i_{P,XI}$, $i_{P,XS}$, $i_{P,BM}$
II	N	$S_{NH4,1}$, $S_{NO3,1}$, $S_{NH4,2}$, $S_{NO3,2}$, $S_{NH4,3}$, $S_{NO3,3}$, $TN_{,5}$, $S_{NH4,5}$, $S_{NO3,5}$	k_H, K_O, μ_H, $\eta_{NO3,H}$, b_H, $K_{NH,H}$, μ_{AUT}, Y_H, f_{XI}, F_{SA}, f, $i_{N,XI}$, $i_{N,XS}$
III	COD	$COD_{TOT,1}$, $COD_{TOT,2}$, $COD_{TOT,3}$, $COD_{SOL,3}$, $COD_{TOT,5}$	k_H, μ_H, b_H, $K_{NH,H}$, μ_{AUT}, Y_H, β, f
IV	MLSS	MLSS,1, MLSS,2, MLSS,3	k_H, μ_H, f_{XI}

- 24 model parameters selected as influential
- good consistency with the relevant processes occurring in each plant section

Calibration order:

The average sum of the βi of each sub-group (β_M) has been calculated. The order of the different calibration sub-groups has been established by ranking the calibration sub-group with respect to β_M. The model output sub-groups were ranked on the basis of the β_M values. The first calibration order has been assigned to the sub-group which presents the highest β_M value.

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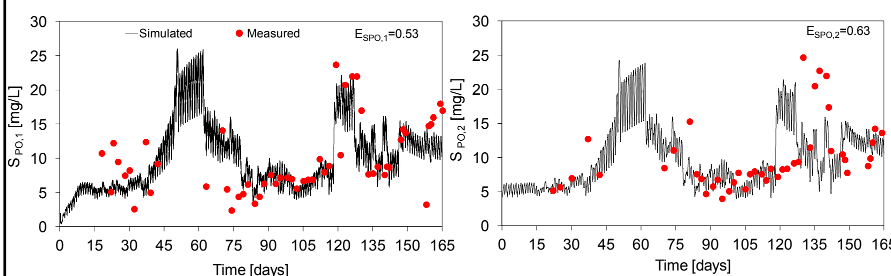
Protocol applications *Example 2: Results phase 2*



Satisfactory results: the efficiency of the 21 model outputs range between 0.2 and 0.7 (maximum value = 1)

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Conclusions

- The proposed protocol has the advantage to perform the sensitivity analysis considering different plant sections, in this way it is possible to better interpret the connections between parameters/processes/outputs
- The proposed protocol has provided acceptable results for full scale and pilot scale modelling applications, using local and global sensitivity analysis
- In view of its high potentiality the protocol has been applied in river modelling (Mannina, 2011), further investigations have also been performed in the WWTP modelling field (other case studies; uncertainty analysis…). The protocol has provided acceptable results!