Improving the parameter identifiability of a watershed scale wastewater infiltration model

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Abstract
Wastewater infiltration poses a potential threat to groundwater and river water quality, especially in regions with low sanitation service levels or pristine water resources. Currently few catchment scale models address this pollution pathway explicitly. In this study we present an evaluation of the onsite wastewater systems algorithm implemented in WARMF / SWAT watershed models. 14 parameters control the process description of water and mass transport, bacterial biofilm evolution and pollutant fate. The code is debugged and adapted for processing in the R language flexible modeling environment. Evaluations are performed for three different result subsets, representing the phases of biofilm initialization, established operation and wash-out events by storm water percolation. Algebraic evaluation of the system of equations reveal strong clustering of parameters related to biofilm development and water constituent fate respectively but little relation between these clusters. Global and local sensitivity analysis show that, except sloughing rate coefficients and BOD conversion rate, all parameters are highly specific to one or two target variables. Bivariate sensitivity analysis confirms the findings of the algebraic evaluation, 8-12 of the parameters are strongly correlated with a coefficient higher than 0.99 to at least one other. Identifiable parameter sets are not found if six parameters or more are included in the calibration. The study shows the high potential for simplification in algorithms of wastewater infiltration on catchment scale. Despite detailed process representation of the examined code, few parameters are sensitive and specific in their effect on the target variables. An aggregated version of the algorithm with only seven parameters allows for the same model flexibility while being much more identifiable. The outlined procedure is transferable to other environmental models for the purpose of performance driven model simplification.

Keywords
wastewater infiltration, watershed model, parameter identifiability, parameter sensitivity

INTRODUCTION

Sanitation systems that infiltrate of treated, pretreated or untreated wastewater are still the globally most frequent type of wastewater disposal (estimated from joint assessment of WHO (2013) and Baum et al. (2013)). In developing countries pit latrines are the predominant disposal type (Graham et al. (2013)), while in industrialized countries a multitude of decentralized or onsite wastewater systems (OWS) have been established. Throughout the last decades significant effort was invested to improve the reliability and efficiency of these systems.

In contrast the research about the processes and effects of infiltrated wastewater on groundwater and surface water resources gained much less attention. Nitrogen species, pathogenics and trace contaminants are mentioned as primary threads from wastewater infiltration. In particular nitrate Wakida and Lerner (2006) point out the importance of different urban emission sources on nitrate contamination of the groundwater. Various monitoring studies confirm the effect for pit latrines (Graham et al. 2013) as well as for advanced onsite treatment systems (Harris 1995) especially in areas with shallow aquifer level and high density of infiltration systems. The detected extent of impact from the systems ranges from few meters to kilometres, environmental boundary and removal efficiencies in the system conditions are cited main influential factors. Modelling the contribution of decentralized wastewater infiltration to nitrogen emissions on watershed scale remains highly uncertain (Helm et al. 2013)

MATERIAL AND METHODS

Onsite wastewater module

The implementation of onsite wastewater systems algorithm in SWAT watershed model (Arnold et al. 1998) was conducted and demonstrated in a case study by Jeong et al. (2011), where the is discussed in detail. It consists of five mayor steps per time step: soil water balancing, biofilm dynamics, plaque dynamics, decay reactions and soil property dynamics. Model parameters comprise: *BzThk* (biozone thickness *[L]*), *BODLB* (BOD to live bacteria conversion rate *[-]*), *RespR* (bacteria respiration rate coefficient *[T^{-1}]*), *MortR* (bacteria mortaility rate coefficient *[T^{-1}]*), *LSlgR* (bacteria linear sloughing rate coefficient *[T^{-1}]*), *ESlgR* (bacteria exponential sloughing rate coefficient *[T^{-1}]*), *TSSPlq* (TSS to plaque conversion rate), *LFC* (linear field capacity coefficient *[-]*), *EFC* (exponential field capacity coefficient *[-]*), *BioD* (biomass density [M/L^3], *BODDR* (BOD decay rate coefficient *[T^{-1}]*), *FCDR* (fecal coliform decay rate coefficient *[T^{-1}]*), *NitDR* (nitrification rate coefficient *[T^{-1}]*), *DenDR* (denitrification rate coefficient *[T^{-1}]*).

Parameter sensitivity and identifiability

For this work sensitivities are used in a normalized, dimensionless form. Global and local sensitivity analysis are performed in order to rank the significance of parameter impact under four different boundary conditions. First year and following years are separated in order to account for the phases of biofilm development and equilibrium state. Sensitivities towards measureable output variables measurable variables (BOD5-, fecal coliform-, ammonia- and nitrate concentration) are subset from all output variables (additionally dead and live bacterial biomass, field capacity and moisture content of the biofilm zone) in order to evaluate potential model benchmarking in an experimental setup. Collinearity is a measure of linear dependence between parameters subsets. It is calculated as a function of the eigenvalue of the sensitivity matrix columns. The higher the value, the more the parameters are related and output variables are affected in a similar way by parameter changes. According to the collinearity definition by Brun et al. (2001), collinearity indeces that exceed a value of 20 are not identifiable.

RESULTS AND DISCUSSION

Parameter interrelation

Table 1 Interaction matrix of all parameters in the wastewater infiltration module, parameter clusters are highlighted in grey.

	BzThk	BODLB	RespR	MortR	LSlgR	ESlgR	TSSPlq	LFC	EFC	BioD	BODDR	FCDR	NitDR	DenDR
BzThk										1	1	1	1	1
BODLB			1	1	1	1								
RespR		1		1	1	1								
MortR		1	1		2	2	1							
LSlgR		1	1	2		2	1							
ESlgR		1	1	2	2		1							
TSSPlq				1	1	1								
LFC									1	1				
EFC								1		1				
BioD	1							1	1					
BODDR	1													
FCDR	1													
NitDR	1													
DenDR	1													
interaction	5	4	4	7	7	7	3	2	2	3	1	1	1	1

Tab. 1 shows the interaction of parameters within the system of equations, the numbers in the fields express co-occurrences of parameters in an equation. Apparently three clusters of interrelated parameters occur. The biggest cluster, highlighted in dark grey, connects parameters related to the growth and decay of the biofilm, the medium grey cluster connects parameters of soil properties with biomass density, while the light grey cluster connects decay parameters with biofilm density and thickness.

The sensitivity analysis demonstrates that clustered parameters are also highly correlated. Especially if only measurable output variables are included for sensitivity determination. Correlation is higher for the equilibrium phase than during biofilm development.

The Fig. 1 visualizes the relation between the number of parameters included in the variation study and the resulting identifiablity. If more than two parameters are varied, the majority of combinations is not identifiable. With six parameters and more included no combination obtains a collinearity index below the identifiablity sill.

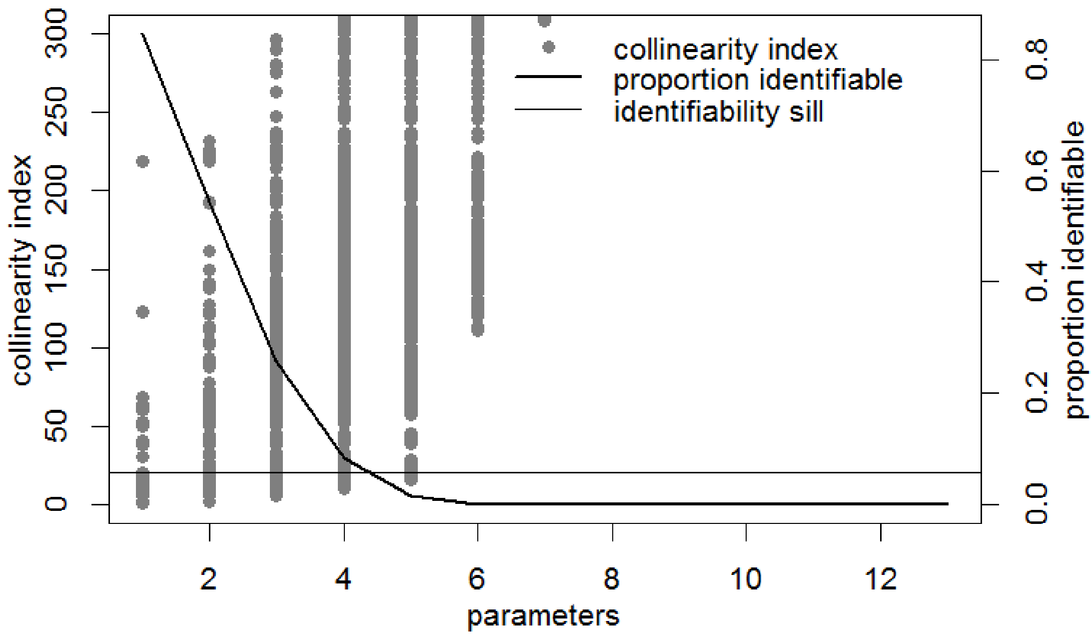

Figure 1. Collinearity of the wastewater infiltration module as a function of the number of parameters included.

Model structure improvement

An improved algorithm for onsite wastewater infiltration is suggested based on parameter interaction, sensitivity and identifiability. *CBODLBB, BioD and CFCBDR* are directly linked and may be substituted by a single parameter. In the same way *BzThk, CRespR, CMortR, LCSlgR, ECSlgR* and *LCFC* can be aggregated with minor rearrangements in the system of equations of the original SWAT source code. The resulting algorithm shows the same global sensitivity and is assumed to be equally adaptable to different boundary conditions. With only seven parameters instead of the original 14 model identifiability is largely improved. A drawback may be that the new aggregated parameters are more difficult to interpret and thus the adjustments during calibration are more difficult to regiment.

CONCLUSIONS

The present work presents a parameter study on the wastewater infiltration module of a catchment scale water quality model. Parameter interaction, sensitivity and identifiability are determined under in order to prioritize modelled processes and simplify model structure. The procedure enables to condense the model algorithm from 14 to seven parameters while improving model identifiability.

In order to further improve model assumptions about wastewater infiltration processes laboratory and field scale experiments are needed. Spatially and temporally resolved observation of BOD5, nitrogen and fecal coliform concentration would offer a valuable possibility to verify the findings from this work. The methodical approach is transferable to other models and model routines for performance driven model simplification.

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