PondR: a process-oriented model to simulate the hydrology of drainage ponds

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ABSTRACT

Drainage ponds are a useful measure to manage water resources. However, these small water bodies are characterized by highly dynamic internal processes. This article discusses a simple process-oriented model developed to simulate temporal dynamics of internal processes within drainage ponds. The *PondR* model is able to simulate the relevant hydrological processes of the pond by using commonly available input data. For model development, data from a 3-year monitoring campaign of the investigated drainage pond served to validate the newly developed model for the autumn and winter time periods. A temporal parameter sensitivity analysis (TEDPAS) revealed that groundwater parameters are predominant during the whole year. The model performed well in simulating outflow together with simulated pond volume and improved the understanding of the hydrological regime for drainage ponds. Regarding the practical benefit, the developed *PondR* model could be useful in future studies for more precise planning of pond dimensions and water resource management in the field of research and engineering services.

Key words | drainage pond model, *PondR*, TEDPAS, water balance

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INTRODUCTION

Ponds have a wide range of meaningful functions in the environment. Besides managing water volumes, Trepel (2016) proposes approaches such as drainage ponds (Steidl *et al.* 2011) or reactive ditches (Pfannerstill *et al.* 2016) to reduce diffuse agricultural inputs to achieve the goals of the European Water Framework Directive (WFD). As examples in Sweden show, semi-natural drainage ponds are becoming increasingly important as nutrient removal measures for farmers and natural managers in highly productive areas. Hydrological boundary conditions such as retention time and storage volume need to be fulfilled to reach an efficient pollutant retention as they exist in wetlands or controlled drainage ponds. The hydrological processes are related to free water surface constructed wetlands (Persson & Wittgren 2003; Vymazal & Brezinova 2015). Created drainage ponds follow the same approach as managed agricultural wetlands (Díaz *et al.* 2012). Both receive periodic flood pulses from drainage pipes (Díaz *et al.* 2012) and depend on local weather conditions as well as environmental conditions (Kehl *et al.* 2009). The rather semi-natural system reacts immediately on site-specific situations, i.e. water level changes than other treatment technologies (Kehl *et al.* 2009). The advantage of drainage ponds is the need of only a limited space (Trepel 2016) and their simple operation. The ponds can reach retention efficiencies that are comparable to larger wetland areas (Díaz *et al.* 2012), when fulfilling certain hydrological requirements.

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Hence, mapping the system-relevant hydrological drainage pond processes is a prerequisite to plan and rebuild pond sites which meet the required functions to gain an improved understanding of internal pond mechanisms. To discuss different uses, functions and designs of pond types in the environment, it is important to understand its hydraulic and hydrological system (Wörman & Kronnäs 2005; Abbas *et al.* 2006; Petru *et al.* 2014). Several studies investigating pond-design options exist (Abbas *et al.* 2006; Kehl *et al.* 2009; Ho *et al.* 2017). Persson & Wittgren (2003) state that the hydrological component in pond design is often highly simplified (Kehl *et al.* 2009) and poorly performed (Konyha *et al.* 1995). Commonly used are the hydraulic parameters loading rate and detention time for pond design (Werner & Kadlec 2000; Wörman & Kronnäs 2005; Ho *et al.* 2017). Additionally, the above-mentioned parameters should only be used in steady flow systems like flow controlled constructed wetlands (Werner & Kadlec 2000). For wetlands and ponds with periodic agricultural drainage discharges (Arheimer & Wittgren 2002), they are rarely flexible to display the variability of the hydrological regime (Kadlec 2010). Appropriate process-based pond models are a promising option to consider this high variability of the hydrological regime in pond planning.

Findings gained from literature research about existing hydrological pulsed-flow pond models were scarce. We extend the search radius to hydrological pond and free-water-surface constructed wetland models with different uses. Most of the hydrological models were often developed for water bodies receiving steady state flows (Nath & Bolte 1998; Werner & Kadlec 2000; Carleton *et al.* 2001). However, Konyha *et al.* (1995) realized the importance of detailed hydrological budget records for wetland planning. They developed a continuous model (SWAMPMOD) to simulate wetlands in a daily resolution. The wetland model is able to simulate dynamic water storage by crucial variables as inflow pathways, precipitation, evaporation and outflow. The routine was tested on a hypothetical shallow and small event-driven storm water wetland. Pandey *et al.* (2006) developed a dynamic water balance in daily resolution applied on a rainwater harvest reservoir receiving discharges from a connected rice field. A relation between reservoir area and water depth is delineated to predict optimum reservoir sizes for rainwater storage depending on the farm size. Kadlec (2010) follows the approach of Konyha *et al.* (1995) developing a continuous dynamic water balance model in hourly resolution with the implementation of stochastic runoff events as driving force (Werner & Kadlec 2000). The aim is to simulate the hydrology of pulsed treatment wetlands in agricultural settings. Water level and volume changes influencing the outflow behaviour were delineated by functions depending on the dynamic water balance for the wetland.

According to Ali *et al.* (2015), also reviewing further approaches, i.e. non-linear artificial intelligence models, we can state the lack of process-based pond models. As presented, water-budget methods were most frequently used for simulating the hydrology of ponds (Ali *et al.* 2015). The main disadvantage is the requirement of considerable input data. Additionally, the available studies often neglect or poorly integrate groundwater processes (Nath & Bolte 1998; Kadlec 2010), i.e. application of constant seepage rates. Further, the investigation of parameter interaction of the modelled pond processes and their influence on the hydrological system is not sufficiently considered. So far, the understanding of the internal pond mechanisms is limited.

Hence, the aim of this paper is to introduce the process-oriented modeling of the pond hydrology as a first step in pond planning for farmers and natural managers. As far as we know, simple process-oriented water-balance models of semi-natural ponds receiving pulsed agricultural discharge are not freely available to the hydrological community.

For further scientific research and pond-dimension planning strategies, there is a strong demand to provide a process-oriented pond model with universal applicability. The model should be capable of considering unsteady drainage flow as water input and groundwater-flow interaction.

To meet these needs, we achieved the following main objectives in this study: to develop a novel drainage pond model named *PondR*; to simulate the relevant hydrological processes of the pond by using commonly available input data; to detect parameters dominating the model performance with a temporal parameter sensitivity analysis (TEDPAS); to explain the most important hydrological processes of a drainage pond; and to allow universal applicability.

METHODS

Model development

To develop a pond model that provides reliable simulation results, we defined three mandatory requirements: (1) time series of observed hydrological processes of a pond; (2) a commonly and freely available programming language; and (3) a verification of the model and its underlying processes.

The drainage pond model *PondR* is conceptualized (Figure 1) as a simple process-oriented approach, enabling the calculation of hydrological mass balances on a daily time step. The inputs for the parameters of the model are mainly observed data and additional data extracted from literature. The developed hydrological model can be applied to different types of ponds. The model code is implemented in the open-source environment R and can be freely adjusted to different site-specific conditions. The derived model structure is tested initially for a pond connected to agricultural tile drainage in a moderate climate zone, with a small surface area (<200 m^2) and shallow groundwater levels.

The volume of the pond is increased by the input of tile drainage inflow and precipitation. The groundwater backflow from adjacent waterlogged areas has an important influence. It is assumed that the embankment of the pond is mainly dammed, if surface flow is absent. Additionally, water loss due to evaporation and groundwater flow is considered. The pond volume is considered as dynamic and is related to the daily changing water level.

The basic model concept includes the hydrological balance equation, Equation (1), for the pond which is based on transport masses of water (m^3). The simulated outflow $V_{outflow}$ is a function of the overall pond volume (Equation (1)), calculated by water balance components. These water balance components include the processes pond volume stored at the day before ($Vsum[_{i-1}]$), inflow volume (V_{inflow}), precipitation volume ($V_{precipitation}$), evaporation volume ($V_{evaporation}$), and groundwater volume ($V_{groundwater}$).

$$Voutflow_{[i]} = f\Big(Vsum_{[i-1]} + (Vinflow_{[i]}) + (Vprecipitation_{[i]}) - (Vevaporation_{[i]}) \pm Vgroundwater_{[i]}\Big) \qquad (1)$$

The simulated pond volume ($Vsum[_{i}]$) of the day is calculated by Equation (2), whereby the current water storage in the pond is reduced by the simulated outflow ($Voutflow_{[i]}$).

$$\begin{aligned} Vsum_{[i]} = {} & Vsum_{[i-1]} + (Vinflow_{[i]}) + (Vprecipitation_{[i]}) \\ & - (Vevaporation_{[i]}) \pm Vgroundwater_{[i]} \\ & - Voutflow_{[i]} \end{aligned} \qquad (2)$$

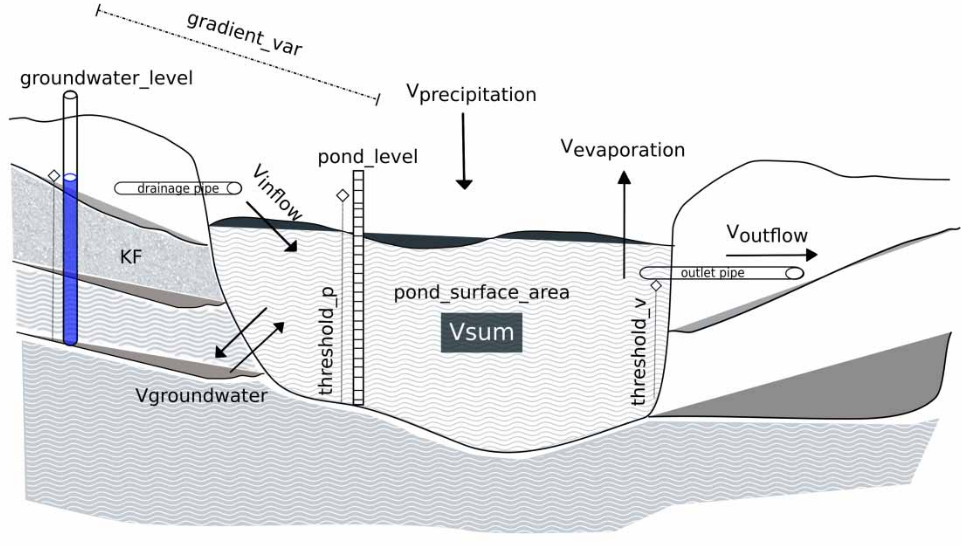

Figure 1 | Concept of the drainage pond model *PondR* considering parameters influencing hydrological processes.

Pond volume and pond surface area

Input parameters of daily pond surface area and daily pond volume are important for an adequate calculation of evaporation and precipitation. The pond surface area and pond volume are calculated dynamically as a function of the pond level. In order to simulate a realistic pond geomorphology both the water-level change within the pond and flood plains, which could be observed during our field study, shall be considered by the model. For water depths below a certain observed pond level ($pond\_level_{[i]} < threshold\_p$), a regression is derived by observed data for the pond that is under investigation (Equation (3)). The *threshold_p* value is recorded in a situation where the pond is nearly filled with water. Above the measured threshold, the gradient of the bank distributes uniformly. On-site, we monitored evenly rising flood plains. In cases of $pond\_level_{[i]} > threshold\_p$ (Equation (4)), it is assumed that the pond surface area is rising with a 0.5 cm buffer accompanied by a 1 cm increase of the pond level.

if $pond\_level_{[i]} < threshold\_p$

$$\begin{aligned} pond\_surface\_area_{[i]} &= 0.003\left(pond_{level_{[i]}}\right)^2 + 0.663 \\ &\quad \times pond_{level_{[i]}} + 92.621 \\ pond\_volume_{[i]} &= -0.004\left(pond_{level_{[i]}}\right)^2 + 0.331 \\ &\quad \times pond_{level_{[i]}} + 68.512 \end{aligned} \tag{3}$$

if $pond\_level_{[i]} > threshold\_p$

$$\begin{aligned} pond\_surface\_area_{[i]} &= pond\_surface\_area_{[i-1]} \\ &+ \left(0.2239 \times pond_{level_{[i]}} - threshold_p\right) - 0.0069 \\ pond\_volume_{[i]} &= -5.82 \times pond_{surface_{area[i]}} - 672.44 \end{aligned} \tag{4}$$

with pond_level = pond level of day i (cm)

threshold_p = observed reference pond level (cm)

Inflow and outflow

Drainage inflow values are stored in the parameter *Vinflow* in a daily time step. The outflow is simulated by a logistical growth curve function of the overall pond volume *Vsum* (Equation (1)). The parameter *threshold_v* marks a shift, below no outflow from the pond occurs (Equation (5)) until this *threshold_v* value is reached, and beyond discharge occurs (Equation (6)).

if $pond\_volume_{[i]} < threshold\_v$

$$Voutflow_{[i]} = \frac{1}{\left(1 + \exp\left(-\frac{(\mathrm{x} - \mathrm{alpha})}{\mathrm{beta}}\right)\right)} \tag{5}$$

if $pond\_volume_{[i]} > threshold\_v$

$$Voutflow_{[i]} = \mathrm{a}\left(\frac{(\mathrm{x} - \mathrm{c})}{((\mathrm{x} - \mathrm{c}) + \mathrm{b})}\right) \tag{6}$$

with *threshold_v* = observed reference pond volume (m^3).

This function provides the basis for the hydrological processes of *PondR*, which can be in general transferred to other ponds.

Precipitation and evaporation

For the evaluation, the precipitation data is aggregated to daily values. The amount of precipitation ($Rday[_i]$ (mm d^{-1})) fallen onto the pond surface area is calculated according to the daily pond surface area ($pond\_surface\_area[_i]$ (ha)) and added to the pond volume (Equation (7) according to Neitsch *et al.* 2011).

$$Vprecipitation_{[i]} = 10 \times pond\_surface\_area_{[i]} \times Rday_{[i]} \tag{7}$$

For evaporation, it is assumed that the pond surface area is fully uncovered. The Penman combination method (DVWK 1996, Equation (8)), which considers energy fluxes and aerodynamic components on a daily step for free water surfaces, is chosen for the model (Maniak 1997). The Penman method calculates the potential evaporation *Ew* of the pond (e.g. DVWK 1996, Equation (8)).

$$Ew = \frac{\frac{s \times Rn}{L} \times \gamma \times f(v) \times (es(T) - e)}{s + \gamma} \tag{8}$$

Ew (mm d^{-1}) represents the potential transpiration for a given day, s (hPa/K^{-1}) is the slope of the saturation vapour pressure curve with temperature. *Rn* (Wm^{-2}) expresses the net radiation, L (Wm^{-2}) the evaporation heat of water. Rn/L (mm d^{-1}) is the evaporation equivalent of net radiation. The psychrometric constant γ has a value of 0.65 (hPa/K). The temperature-dependent saturation vapour pressure is expressed by $es(T)$ (hPa). e (hPa) describes the air vapour pressure. The wind function after Dalton (DVWK 1996) is described by $f\ (v)$ (ms^{-1}). The evaporation values Ew (mm d^{-1}) serve as model input variable for the further calculation of the potential evapotranspiration coefficient (Equation (9)). The volume of water removed from the water body by evaporation during the day ($Vevaporation$ (m^{3}d^{-1})) is calculated by Equation (9) (Neitsch *et al.* 2011).

$$Vevaporation_{[i]} = 10 \times \eta \times Ew_{[i]} \times pond\_surface\_area_{[i]} \tag{9}$$

whereas η (–) is the evaporation coefficient with a formalized value of 0.6. Ew (mm d^{-1}) is the potential evapotranspiration coefficient for a given day and *pond_surface_area* (ha) is the surface area of the pond.

Groundwater flow

According to Matthess (1993), groundwater flow *Vgroundwater* (m^3 s^{-1}) is described by a function of the potential difference between the groundwater level (*groundwater_level* (m asl)) and the pond level (*pond_level* (m asl)), the area of groundwater passage (Agw (m^2)) and the coefficient of permeability (KF (m s^{-1})). R (m) describes the horizontal distance between *groundwater_level* and *pond_level*. Clogging CL describes the minimized permeability between groundwater and surface water because of root growth or sedimentation (m (Equation (9))). KF and CL control the daily amount of groundwater flow. A higher KF increases the velocity of soil-passing water reaching the groundwater. A higher CL value minimizes the groundwater area corresponding to a decreased groundwater flow. A dynamic groundwater area A_{gw} (m^2) depending on groundwater level fluctuations is calculated in Equation (10), assuming a varying groundwater area, which influences the amount of groundwater entering the pond.

$$A_{gw} = soil\ layer_{impermeable} - \ groundwater\ level\ \times KL \tag{10}$$

The height of the impermeable soil layer (m) reduced by the daily effective groundwater level (m asl) is multiplied with clogging extent (CL) to calculate Agw (Larson *et al.* 2000).

$$Vgroundwater = KF \times \left(\frac{\frac{groundwater\_level^2}{2} - \frac{pond\_level^2}{2}}{R + CL} \right) \times Agw \tag{11}$$

The potential gradient between groundwater level and pond level is covered by the parameter *gradient_var*, to cope with uncertainties of water depths. The potential gradient regulates the amount of groundwater flow and the flow direction depends on the level relation between groundwater and pond.

Model application

Study site

As typical for the North German Plains, the surrounding area of the drainage pond is characterized by a flat topography, small hydraulic gradients and shallow groundwater levels. The studied drainage pond has an average surface area of 130 m^2. The field area slopes northward to the pond and the surrounding vegetation belt is missing at the drainage pipe. The drainage pipe discharges water from the field northwards directly into the pond. The outflow drains off to a ditch.

Input data

A time series from October 2011 to December 2014 is available for this pond, including inflow, outflow, precipitation, groundwater and pond levels (Table 1). Water levels are manually measured with a gauge that is installed within the pond. The successive change of 1 cm pond level led to a pond surface change of 0.22 m^2 and a pond volume change of ~1.3 m^3. The discharge from inflow and outflow of the pond is measured by collecting water with buckets. Precipitation data are taken from a tipping bucket rain gauge in a half-hourly resolution located about 1.4 km to the pond. The groundwater level is measured by an electric contact gauge.

Table 1 | Set of input data observed at the investigated drainage pond between the years 2010 and 2013

Input data	Units	Monitoring phase
Inflow	$m^3\ d^{-1}$	2010-08-23 to 2012-06-11; 2012-10-18 to 2013-01-03; 2013-04-17 to 2013-14-05; 2013-09-30 to 2013-09-27
Precipitation	$m^3\ d^{-1}$	
Outflow	$m^3\ d^{-1}$	
Pond level	m asl	2012-10-18 to 2013-01-03; 2013-04-17 to 2013-14-05
Groundwater level	m asl	2012-10-18 to 2013-01-03; 2013-04-17 to 2013-14-05; 2013-09-30 to 2013-09-27
Volume	m^3	2013-11-15
Surface area	ha	2013-11-15
Evaporation	$m^3\ d^{-1}$	Input data for calculation provided in daily resolution by German Weather Service for station Schleswig from 2010-08-23 to 2012-06-11; 2012-10-18 to 2013-01-03; 2013-04-17 to 2013-14-05; 2013-09-30 to 2013-09-27
KF	$m\ s^{-1}$	2013, borehole geophysical method
Impermeable soil layer	m	2013, Pürckhauer drilling

Temporal parameter sensitivity analysis

A proper integration of model parameters and its underlying processes is a prerequisite to achieve reliable model results (Pfannerstill *et al.* 2015). In this study, we use a TEDPAS to obtain temporal dynamics of parameter sensitivity (TEDPAS; Reusser *et al.* 2011) for the verification of the newly developed model. TEDPAS supports to gain knowledge about the parameter dominance and the parameter behaviour of models (Guse *et al.* 2014; Pfannerstill *et al.* 2015). In this study, TEDPAS is used to verify proper parameter integration into the model and to obtain knowledge about the most important parameters for model calibration.

TEDPAS makes use of the variance-based Fourier amplitude sensitivity test (FAST), which is suitable for non-linear models requiring only a few model runs (Reusser *et al.* 2011). We use the R-package FAST (Reusser 2013), which contains FAST and is thus easily applicable to models that are implemented in R. For TEDPAS, parameters and physically reasonable parameter ranges for the most important model processes were selected as a precondition to perform the temporal parameter sensitivity test. The number of model runs depends on the selected number of model parameters (Cukier *et al.* 1978). A Fourier parameter set was generated for the sensitivity test, which contains the combination of all parameter frequencies. Each parameter combination was finally applied to the model to obtain temporal dynamics of parameter sensitivity, which provide information about the dominance of different model components as represented by individual model parameters for different time periods (Reusser *et al.* 2011; Guse *et al.* 2014).

TEDPAS uses daily model results as target variable, which is most often discharge. In our study, six model parameters (Table 2) are selected to perform the temporal parameter sensitivity test to the model. The mentioned parameters are assumed to be relevant for process description. The parameters cover all hydrological processes such as groundwater flow, evaporation, drainage inflow and precipitation and the input parameters *KF, CL, groundwater_level*, V*inflow, Vevaporation* and V*precipitation* and are thus helpful to verify proper process integration into the model structure. To perform the sensitivity test, parameter values are varied by add-subtraction and by a multiplication factor (Table 2). The daily sensitivity distribution is calculated for the simulated model output parameter *Voutflow*. To cover the whole parameter space using FAST, 91 model runs are necessary in our study.

Model calibration and evaluation

In this study, the calibration is carried out for times series from 26th September 2011 to 30th April 2012 by manually changing dominant parameters within the selected ranges from the TEDPAS. The best calibration results are determined by integrating qualitative and quantitative

Table 2 | Set of model parameters: default values, selected ranges for TEDPAS, and final calibrated values (with obs. ts. = observed values of times series, r = range parameter, as = add/subtraction parameter)

				TEDPAS variation					
Parameter definition	**Abbreviation**	**Process**	**Default value**	**Range**		**Type**	**Final value**	**Unit**	**Equation**
Clogging	CL	groundwater	42 measured/estimated	20	60	r	**42**	m	11
Coefficient of permeability	KF	groundwater	0.003 measured/estimated	0.0001	0.001	r	**0.0004**	$m\ s^{-1}$	11
Distance pond water level to groundwater level	R	groundwater	10.6 measured/estimated	–	–	–	**10.6**	m	11
Modified groundwater level	gradient_var	groundwater		−0.2	0.2	as	**0.02**	m	11
Lower limit of groundwater area	$soillayer_{impermeable}$	groundwater	1.17 measured/estimated	–	–	–	**1.20**	m	10
Variation of evaporation	evap_var	evaporation	obs.ts.	−0.01	0.01	as	obs.ts.	m^3	9
Variation of inflow	drain_var	drainage flow	obs ts.	−5.0	5.0	as	obs.ts.	m^3	1
Variation of precipitation	prec_var	precipitation	obs ts.	−0.03	0.03	as	obs.ts.	m^3	7

knowledge (Seibert & McDonnell 2002; Pfannerstill *et al.* 2017), which is provided by model structure understanding, considering the quality of the data and the catchment characteristics together with their underlying theory of process knowledge (Boyle *et al.* 2000). For model validation, time series from 30th September 2013 to 27th December 2013 are selected. The statistical criteria NSE (Table 3) and PBIAS (Table 3) are used to evaluate the model performance. In terms of model evaluation, flow duration curves (FDCs) are increasingly used as a signature for different processes (Yilmaz *et al.* 2008; Pfannerstill *et al.* 2014). By subdividing the FDC into segments, different magnitudes can be evaluated individually.

The graphical evaluation is performed with hydrographs and FDCs. The FDCs are divided into three discharge segments Q0–Q20%, Q20–Q70% and Q70–Q100%. The flow periods are compared by the criteria RSR (Table 3) to allow a fair comparison between different magnitudes (Pfannerstill *et al.* 2014).

RESULTS AND DISCUSSION

Results

Temporal parameter sensitivity analysis

The temporal parameter sensitivity revealed the dominant model parameters/processes and provided knowledge about the parameter behaviour. The relationship between the parameters and their relevance for process representation in the model is illustrated in Figure 1 with respect to the output parameter *outflow*.

The temporal sensitivity of the parameter *drain_var* is low (Figure 2(b)). However, in spring and summer months the sensitivity increases to a maximum, which suggests rising relevance of tile drainage input into the pond especially at very low outflow discharges, increased air and pond water temperatures and evaporation. The variations of evaporation (*evap_var)* and precipitation (*prec*_var) show a very limited sensitivity against the model output (Figure 2(c)). The groundwater parameter *gradient_var* was highly sensitive to most of the time, especially in phases of rising direct runoff (Figure 2(b)) and higher pond volumes. The

Table 3 | Summary of model performance and distribution of simulated pond balance components for calibration and validation period

	Model performance							Hydrological pond balance components									
								Input (m^3)					Output (m^3)				
Time series	Output parameter	NSE	PBIAS	Output parameter	RSR Q0-20%	RSR Q20-70%	RSR Q70-100%	Output parameter	$\sum$	V_{inflow}	$V_{groundwater}$	$V_{precipitation}$	$\sum$	$V_{outflow}$	$V_{groundwater}$	$V_{evaporation}$	ΔV
Calibration	outflow	0.85	−0.8	obs/sim outflow	1.88	0.65	0.38	outflow	6,560.0	5,563.0	941.0	56.0	7,071.0	7,047.0	0.0	24	511
	volume	0.86	−11.2	inflow/ sim outflow	0.91	0.58	1.03	volume	100%	84.8%	14.3%	0.9%	100%	99.7%	0.0%	0.3%	7.2%
Validation	outflow	0.73	−5.5	obs/sim outflow	0.45	0.25	0.61	outflow	4,656.2	3,344.2	1,279.1	32.9	4,463.2	4,438.0	16.2	9.6	193.2
	volume	0.96	− 1.4	inflow/sim outflow	6.62	0.88	0.18	volume	100%	71.8%	27.5%	0.7%	100%	99.4%	0.4%	0.2%	3.1%

parameters representing the process of groundwater flow show an important impact on the observed model output decreasing sensitivity for drier summer months. The groundwater flow situation depends on the daily fluctuating relation of pond water- and shallow groundwater levels (Figure 1). The sensitivity of the groundwater parameter *KF* was quite low, but showed a temporal dynamic and increased to a maximum during baseflow periods and in times of low precipitation (Figure 2(a)). The trend of *KF* was opposed to the course of *gradient_var*. The parameter *CL* showed no sensitivity against the model output (Figure 2(a)).

Model calibration and evaluation

Based on the results of the TEDPAS, the parameters *KF* and *gradient_var* were considered for manual calibration (Figure 2(d)). The best result was found by setting the hydraulic conductivity parameter *KF* to 0.0004 m s^{-1}, which was validated by the auger hole method in the field nearby the pond. The value of the impervious layer parameter *lowerlimit* is estimated by local drill test. The potential gradient between pond level and groundwater level was set to 0.02 m asl (Table 1). For the completion of the water balance simulation, groundwater inflow was considered for the calibration period by simulating a groundwater influx of 4.3 ± 2.0 m^3 d^{-1}.

The clogging parameter *CL* was set to the observed field value of 42 m. The parameter $soillayer_{impermeable}$ reflects the height of the impervious soil layer in the model and was set to 1.20 m. The parameter *R*, which represents the distance between pond water and groundwater level, was set to the measured distance of 10.6 m.

The simulated hydrographs reproduce the dynamic of the pond volume (Figure 3(a)) and the outflow of the pond (Figure 3(b)) during the calibration period. The model performance (Table 3) is satisfying with respect to the pond volume (NSE = 0.85, PBIAS = −0.8) and the performance of outflow simulation (NSE = 0.86, PBIAS = −11.20) with slight over- and underestimations.

The observed and simulated FDCs depict the proportion of the observed drainage pond inflow (used as model input) to the simulated outflow (Figure 4(b)). It was shown that the simulated outflow (Figure 4(a)) underestimated high peaks

(Q0-Q20%, $>30\ \mathrm{m^3\ d^{-1}}$, RSR = 1.88). An overestimation of small observed outflow values (Q70-Q100%. $<0\ \mathrm{m^3\ d^{-1}}$, RSR = 0.38) was identified (Figure 4(a)). A continuous underestimation of the inflow against the simulated outflow values was observed in all segments, especially for small ($<20\ \mathrm{m^3\ d^{-1}}$, see RSR = 0.91) and high (Q0-Q20%, $> 40\ \mathrm{m^3\ d^{-1}}$, see RSR = 1.03) water amounts (Figure 4(b)).

The quantitative water balance components for the calibration period (Table 3) can be summarized as follows: The drainage inflow (84.8%) and the groundwater influx (14.3%) accounted as dominant input factors. The impact of precipitation was below 1%. During the considered time period, no groundwater outflow was calculated, thus, the share of the pond outflow amounted to 99.7%. The remaining amount of water can be accounted for 0.3% by evaporation.

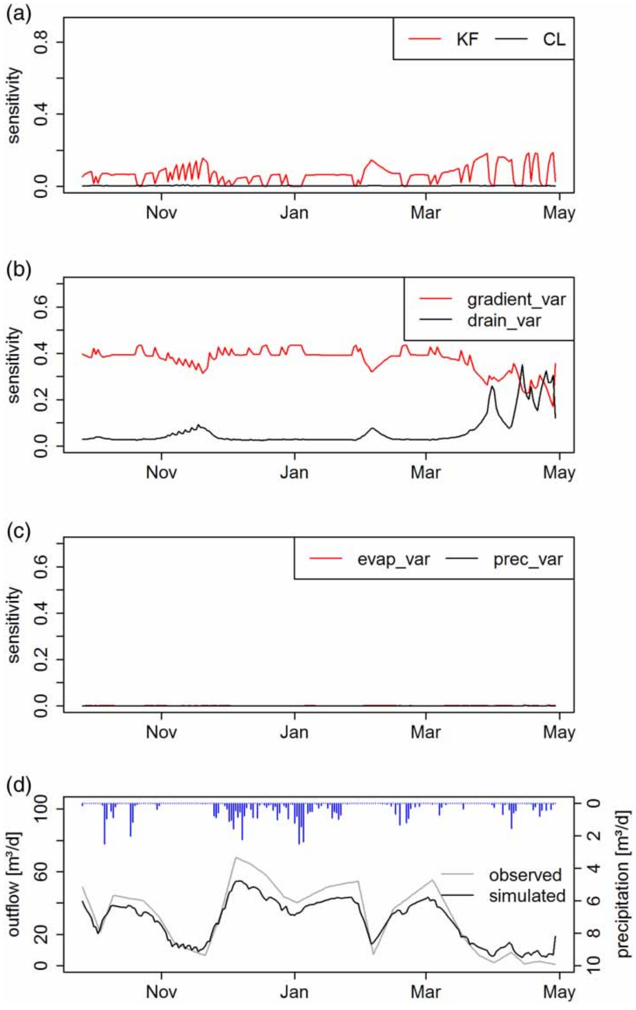

Figure 2 | Temporal parameter sensitivities for simulated outflow of the pond from 2011-09-26 to 2012-04-30. The subplots (a)–(c) contain two model parameters: KF (coefficient of permeability), CL (clogging), gradient_var (modified potential gradient of levels), drain_var (variation of inflow), evap_var (variation of evaporation), prec_var (variation of precipitation); (d) displays observed/ simulated outflow and precipitation.

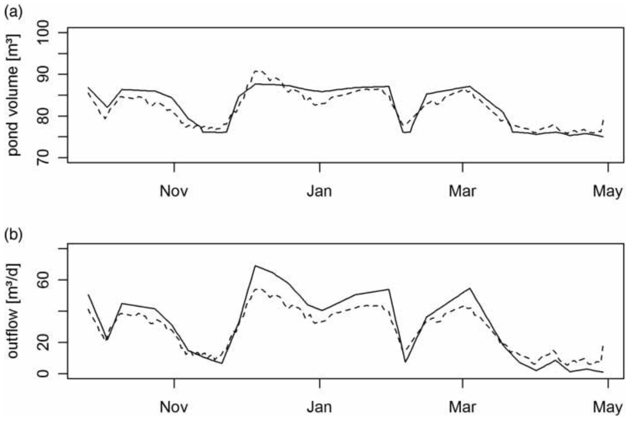

Figure 3 | (a) Simulated (dotted) and observed (straight line) pond volume and (b) the outflow for the calibration period (2011-09-26 to 2012-04-30).

For the validation period, the model performance (Table 3) of the reproduction of the pond volume dynamics and the pond outflow was satisfying (NSE = 0.73, NSE = 0.96). The negative PBIAS of 1.4 indicated an underestimation of the observed outflow values (Figure 5). The simulated groundwater flow direction fluctuated, however, the groundwater flow entering the pond was predominant (15.4–95.7 $\mathrm{m^3\ d^{-1}}$).

Regarding the FDCs (Figure 6), it was detected that the simulated outflow underestimates flows between 40 and

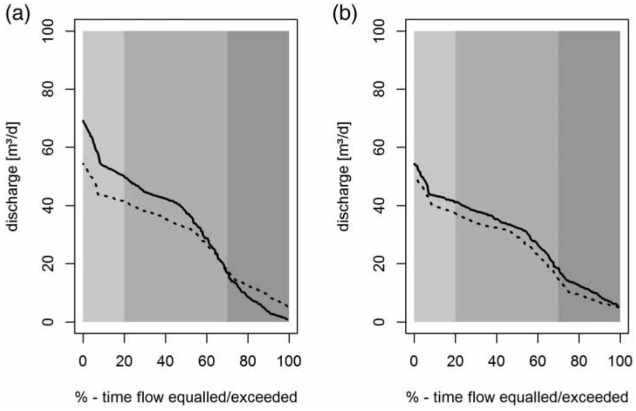

Figure 4 | FDC for (a) the observed (straight line) and simulated (dotted line) outflow and (b) the observed drainage inflow and simulated outflow for calibration period (2011-09-26 to 2012-04-30).

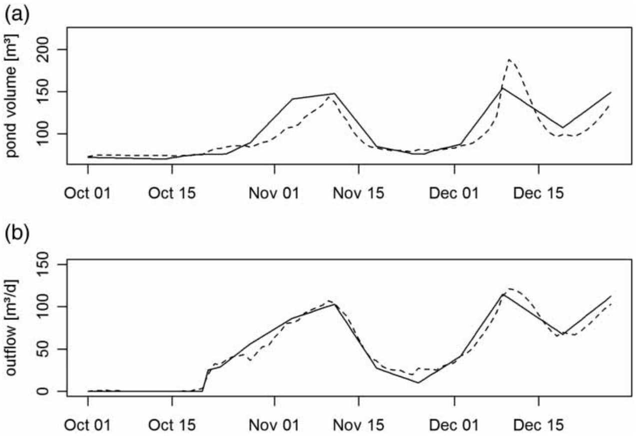

Figure 5 | (a) Simulated (dotted) and observed (straight line) pond volume and (b) the outflow for the validation period (2013-09-30 to 2013-12-27).

$70\,\mathrm{m}^3\,\mathrm{d}^{-1}$ of the observed outflow. An overestimation of low ($<40\,\mathrm{m}^3\,\mathrm{d}^{-1}$, RSR: 0.61) and very high outflows ($>70\,\mathrm{m}^3\,\mathrm{d}^{-1}$, RSR: 0.45) can be identified (Figure 6(a)).

The performance during the validation improved for all segments of the FDC in comparison to the calibration period (Figure 6(a)). Considering the observed inflow and the simulated outflow (Figure 6(b)), a strong overestimation of the inflow against the simulated outflow values was obtained for high water amounts (RSR = 6.62, Figure 6(b)). The dominant hydrological components for incoming water fluxes (Table 3) were the drainage inflow (71.8%) and the groundwater influx (27.5%). The impact of the precipitation amount was below 1.0%. The share of the outflow was 99.4%. The remaining water was lost by groundwater outflow (0.4%) and evaporation (0.2%).

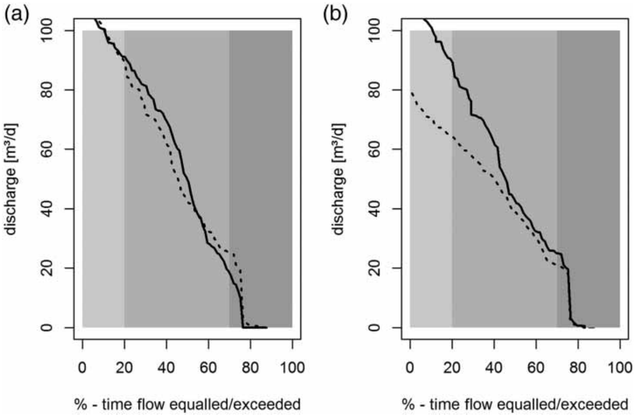

Figure 6 | Flow duration curves (FDC) for (a) the observed (straight line) and simulated (dotted line) outflow and (b) the observed drainage inflow and simulated outflow for validation period (2013-09-30 to 2013-12-27).

DISCUSSION

Verification of processes, parameter dominance and behaviour

The model reliability is verified by evaluating the model behaviour with respect to process representation, parameter dominance, and model parameter. In general, the modelled drainage pond outflow, expressed by the output variable *outflow,* shows an indirect reaction on precipitation events in the catchment (Figure 2(d)). In fact, with an increased precipitation, the soils connected directly or indirectly with the drainage inflow pipe are more saturated. Consequently, an increased drainage inflow or groundwater inflow to the pond occurs. Thus, the simulated delay of the outflow peaks after precipitation events are reasonable and can be explained by an increased volume of the pond. The model outflow – volume function was verified by the validation period and is therefore a valid relation to depict the hydrologic behaviour of the pond. The reproduction of the pond's outflow behaviour seems to be realistic, since the simulation of pond volume reacts to changes in inflow and outflow dynamics.

Furthermore, the results of TEDPAS (Figure 2) demonstrate that the pond outflow process is mainly determined by the simulated groundwater flow. Hereby, the water gradient between pond level and groundwater level plays the most important role, which is shown by the high sensitivity of the parameter *gradient_var* over the entire period. The parameter *gradient_var*, expressing the difference between pond and groundwater level, contributes strongly to the groundwater flow. The groundwater parameter *gradient_var* regulates the direction of groundwater entering or leaving the pond and the daily amount of groundwater flow. The higher the difference between the levels, the larger the amount of groundwater flows. The sensitivity analysis shows that drier periods with low discharges are regulated by the permeability parameter *KF*. The variation of soil water flow rate parameter *KF* affects the groundwater flow by accelerating or delaying the groundwater flow.

In wetter phases, the groundwater flow is mainly controlled by the parameter *gradient_var* since the negative linear related interaction of both parameters is decreasing and superimposes the sensitivity of *KF*. On the contrary, during dry periods the groundwater flow is rather low, which minimizes the variance of *gradient_var* and ensures that the parameter *KF* has a bigger influence on the model output. Due to the high dominance of *gradient_var*, the other parameters are only relevant if *gradient_var* becomes less important. Here, a clear relationship of *gradient_var* to higher outflows was detected.

The modelled groundwater flow interaction reflects the strong impact of groundwater processes on the outflow over the entire time period. This becomes apparent by the observed outflow surplus in contrast to the amounts of drainage inflow. During wet periods, the model regulates the groundwater flow by an exponential increase of the groundwater level. Consequently, a higher amount of groundwater can enter the pond. This procedure also covers the processes interflow and surface flow, which are considered as an aggregated flux into the pond. It is assumed, that additional high interflows occur during high precipitation and drainage events. Especially the northern pond area around the drainage pipe is probably affected by interflow. Consequently, a highly dynamic regulation for the interaction between pond and groundwater represents this additional, temporary water input into the pond. The groundwater dominance is reflected by the trend of the outflow and volume hydrographs. The daily calculated groundwater flow variability enables the realization of the pulse-modulated outflow and volume courses. Hence, fast and daily changing groundwater influxes to the pond accompanied by area-intensive precipitation events are considered precisely.

The calibration procedure resulted in a satisfying value for the hydraulic conductivity as observed during field measurements. Additionally, permanent effluent conditions in the pond were modelled. The observed higher groundwater levels in comparison to the water levels of the considered drainage pond correspond perfectly to the modelled groundwater situation. In conclusion, the simulated groundwater processes are plausible with respect to observed local shallow groundwater characteristics (Kiesel *et al.* 2010; Pfannerstill *et al.* 2015). The varied values of the parameters *evap_var* and *prec_var* show no influence on the simulated outflow (Figure 2(c)). The very limited sensitivity can be explained by the very small surface area of the pond, which is very little affected by area intensive processes such as evaporation and precipitation. For other studies, it may be possible to neglect evaporation in the water balance, as shown in (Bachand & Horne 2000). However, in this study, there is a low share of evaporation to the hydrological budget (<0.3%) during autumn and winter but evaporation might have a stronger influence during warmer summer months (Tournebize *et al.* 2016). In other studies, an evaporation time series must be provided by the user as model input (Konyha *et al.* 1995; Pandey *et al.* 2006). Therefore, the implementation of the evaporation process as a freely adjustable function of the current pond surface area into the model code was convenient to reach an automated transferability for other pond locations and the adaption to a reduced/risen potential evaporation simultaneously with decreased/increased pond water level. The results of TEDPAS show low sensitivities for the evaporation and precipitation parameter and confirm the low process impact of evaporation and precipitation to the pond model behaviour.

Another important pond process is the inflow of the tile drainage pipe, contributing with 72% (validation period) to 85% (calibration period) to the input components of the pond water balance. Especially in periods with decreased groundwater dynamic and very low inflows, the parameter *drain_var* shows higher contribution to the outflow. The sensitivity reaches its maximum during the late spring months, when the temperatures increase and precipitation decreases. At this time, the inflow of the drainage pipe to the pond gains more importance than the groundwater flow. The decreasing sensitivity of the groundwater parameter *gradient_var* confirms the lower impact of the groundwater process during the summer month. The drainage inputs have a strong influence on pond behaviour, hence, in case of drier periods with warmer temperatures the sensitivity of the *drain_inflow* parameter increases.

It can be identified that groundwater flow during winter months and tile drainage pipe inflow during summer months are the key hydrological components regarding the process understanding of the drainage pond behaviour. Consequently, the developed model operates reliably and refers to real observed tile drainage pond characteristics.

Model performance

The model performance was evaluated using a state-of-the-art multi-objective calibration approach which is focused on the different parts of the hydrograph by using several contrasting objective functions. The discharge dynamic of the pond is reproduced quite well (NSE = 0.96). PBIAS shows potential for model improvements. Predominantly, underestimation occurred during high- and mid-flow periods as indicated by the negative PBIAS. This can be clearly seen by comparing observed and simulated outflow data in the FDC for both time periods. Low discharge is overestimated, moderate and high flows are underestimated. Limitations occurred by simulating high groundwater flows after very strong precipitation events. Simulated groundwater influx maxima occurred and were accompanied by very high inflow, outflow, groundwater- and pond-level conditions. During these extreme situations, the simulated groundwater flow exceeded the inflow and outflow value. The exponential groundwater level modification, which enables the groundwater in general to react reasonably on increased groundwater levels with enlarged groundwater flows, probably leads to overestimated groundwater maxima after very heavy precipitation events. Those extreme values are only an exception. In general, the groundwater level increases in plausible ranges ($<7\ \mathrm{m}^3/\mathrm{d}$) with an increased pond volume. The groundwater flow – volume relation might lead to underestimated groundwater flows during lower pond volumes and to overestimated groundwater flow values during higher pond volumes. Hence, the groundwater simulation has an impact on the model performance with respect to underestimation of low discharges and the overestimation of middle and higher flows. It would be necessary to validate the groundwater volume relation with data from a second groundwater pipe. Additionally, the groundwater interaction with the pond needs to be monitored more precisely, i.e. by an increased monitoring frequency or tracer experiments.

Despite the considered limitations, the implemented groundwater process that is similar to Larson *et al.* (2000) reflects the observed local shallow groundwater characteristics of the study test site quite well (Kiesel *et al.* 2010; Pfannerstill *et al.* 2015). The implemented approach considers soil properties, sediment sealing, a dynamic hydrological gradient and an adjustable groundwater area at the specific pond location. Hence, the included dynamic groundwater flow calculation is progressive in comparison with studies neglecting (Kadlec 2010) or simplifying seepage by constant recharge rates (Nath & Bolte 1998). Particularly in regions with high groundwater–surface water interactions, as in our study test site, a precise groundwater simulation is important.

For the calibration period, a continuous deviation of the inflow to outflow is identifiable. On average, the pond inflow is smaller than the outflow. Considering the validation period, the inflow and outflow amounts differ even more. The gap between inflow and outflow indicates a possible lateral flow, surface runoff or additional groundwater flow entering the pond. Surface flow is possible in low vegetation phases. For surface flow and interflow processes, observed data are not available and consequently, these processes are not implemented in the model. Additionally, uncertainties caused by gauging errors might be possible. Therefore, the model simulates only a reduced outflow surplus than observed.

However, we see some room for model improvement regarding the groundwater simulation. Hence, future studies should improve the groundwater gauging, since groundwater flow modeling is limited due to insufficient knowledge of groundwater flow conditions around the pond. Additionally, surface flow and lateral flow observations could help to identify reasons for deficits in simulating pond outflow and volume simulation.

Model transferability

Through the implementation of dynamic area and volume calculation, potential evaporation estimation, groundwater flow and outflow calculation we considered important key components of the pond hydrology, which have been neglected in other studies. Additionally, the amount of required input data is reduced and it is easier for the model user to apply the model with commonly available data for planning purposes. Further, the dynamic modelling approach provides the possibility to plan the construction or extension of pond sites based on real, long-term natural flow time series in place of rules of thumb and average rates (Konyha *et al.* 1995). For mapping the hydrological conditions in a drainage pond in a precise manner, there was a high demand to implement a realistic and dynamic representation of the pond's geomorphology in the model. Following Kadlec (2010), the surface area and volume were calculated as a function of the daily pond level. The regressions were obtained by a topographic survey. For the user, it is possible to freely adjust the area and volume functions for both already existing ponds in the environment and for pond shape design scenarios (Wörman & Kronnäs 2005; Abbas *et al.* 2006).

Regarding the mentioned options to adapt the model to site-specific conditions, the newly developed *PondR* model provides a simple to operate and validated model structure, which is flexible for various application extensions, e.g. pond design scenarios, nutrient transport and storm water storage. Overall, our study contributes to the linkage between hydrological measurements and hydrological modelling. It is clearly demonstrated how a well constituted measurement campaign and process-based model approach helps to improve the process understanding in hydrology. We see a strong coincidence of measurements and modelling as a profound step for future diagnostic studies in hydrology.

CONCLUSIONS

In this study, a simple process-oriented water balance model (*PondR*) focussing on simulation of semi-natural drainage ponds was developed. The aim of this is to provide a tool to simulate the hydrology of pulsed-flow drainage ponds. To these ends, the internal hydrological processes of the pond were investigated and its appropriate integration into the model was verified. The model is based on a balance equation considering inflow, evaporation, precipitation, and groundwater. The outflow is calculated as a function of the overall pond volume.

A TEDPAS revealed that the groundwater flow is the dominant process for regulating the hydrological regime of the drainage pond. The coefficient of permeability shows high sensitivity in times of base flow and low precipitation. The parameter regulating the gradient between the groundwater and pond water levels is sensitive to rising discharge, pond volume, and stronger precipitation events. According to our analysis of the temporal parameter dominance and the behaviour of the investigated parameters, we conclude that the model plausibility and the functioning of the analysed model parameters are reasonable. The behaviour of the model and the simulated processes are plausible according to the local hydrological conditions.

The calibration leads to a satisfactory model performance of outflow and volume reproduction of the pond both in calibration and validation periods.

Referring to our initial research questions, we conclude that our study results revealed a freely available pond model to the hydrological community, which integrates model equations that require a minimum level of observed data. The model is flexible and can be adapted to site-specific hydrological processes and characteristics, e.g. different pond surface areas, different volume – outflow relations, and hydraulic residence times. Furthermore, the developed model can be easily extended if additional data such as groundwater level observations or observed surface runoff is available. In general, the model may be used for scientific research or water resources management.

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