Author's response

In this document we provide:

- Point by point answer to reviewer's comments (update from the previously uploaded answer).
- The revised manuscript with <mark>changes highlighted in yellow.</mark> Most of the figures (Fig 3, 5 and 6) and tables (Tab. 1,2,3 and 5) have been changes but are not highlighted to improve the clarity of the document.

Answer to the comment by anonymous referee #1

We thank the reviewer for the deep review that will help to improve the quality of the paper and we explain below how we plan to address each of the points raised.

Interactive comment on "Hydrological control of dissolved organic carbon dynamics in a rehabilitated Sphagnum–dominated peatland: a water-table based modelling approach" by Léonard Bernard-Jannin et al.

Anonymous Referee #1

Received and published: 27 November 2017

The ms describes a modeling approach to predict the relationship between DOC production and hydrology, especially water table levels, in a fen which partly experienced draining and restoration. The authors used a parsimonious approach including a hydrological and a biogeochemical component. The model was calibrated directly at the site through monitoring of the peatlands water table level at the two measuring sites and by DOC analyses. In addition the authors carried out fluorescence measurements to determine changes in the DOM quality. In principal, several parsimonious models to predict the release of DOC dependent on hydrological changes from peatlands exist. Different from these models which commonly use discharge data to characterize the hydrological component, the authors use changes in water table to predict DOC release. The authors concluded that their model predicts DOC release at the two sites reasonably well (whatever this means). As an advantage compared to other models they argue that the use of water table changes instead of using discharge measurements allows predicting local changes in DOC release esp. if parts of a peatland underwent draining and restoration, which might have strong influence on DOC production and release. I don't have an emphasis on hydrological modeling of peatlands but on the biogeochemical processes of DOM production on peatlands, so I will not comment on the quality of the model itself.

I had a bit a hard time with the structure of the paper. One reason might be that the mentioned objectives of the study are very general . . . . to identify hydrological processes and factors controlling DOC dynamics . . . . the impact of rewetting on DOC export. It is known that water table changes is the major driver of DOC release in peatlands, because surface wetness determines the redox conditions on the mire's surface which in turn control microbial activity and peat decomposition. In this sense, it would be helpful if the authors could first describe in more detail what they expect the effect of peatland restoration on DOC release could be, especially what is expected how the amount and quality of DOM changes as result of drainage and subsequent rewetting. Based on this it would be easier to understand the chosen approach.

We will add a paragraph in the introduction explaining the expected results of restoration on DOC dynamics based on existing literature. Air Temperature and WTD are considered to be good descriptors for conceptual DOC models (Birkel et al., 2017; Lessels et al., 2015). Indeed these two parameters determine the microbial activity and peat decomposition that are the producing and

consuming processes of DOC in peat water. Concerning studies on the impact of rewetting and drain blocking in peatland on DOC dynamics have shown opposite results with increasing concentrations (Hribljan et al., 2014; Strack et al., 2015) and decreasing concentrations (Höll et al., 2009; Wallage et al., 2006). In this study we propose to use a modelling approach to simulate DOC concentrations in a rewetted peatland and identify factors of control that can explain differences in DOC dynamics. (P2 L17-20, P3 L10-11).

In addition, we will specify the objectives of the study as follow: "The objectives of this study were 1) to identify the dominant hydrological processes in both a rewetted and undisturbed peatland locations, 2) to understand how these hydrological processes affect the DOC dynamics in each of these two locations, and 3) to assess the impact of the rewetting on DOC export in a Sphagnum-dominated peatland" (P3 L16-17)

Moreover, I think that the comparison between the WTD and the stream discharge approach should be discussed in more detail. On page 12 the authors argue that the advantage of the WTD approach is that this model can predict DOC release at different areas in the same peatland in contrast to the stream discharge approach which integrates the entire peatland. However, the authors have only selected a single site with is under restoration and did not define which biogeochemical or hydrological component/factor is specific for the rewetted site. Due to this, it remains unclear how the specific behavior of the rewetted site compares to the overall variation of DOC release and DOM quality during water table changes in the entire peatland (compare the discussion in Birkel et al 2017 and Broder et al . 2015 cited therein).

Two sites were selected, one affected by the restoration and one not affected. Then the model is calibrated for both sites. It is therefore the values of the calibrated parameters (related to hydrological and DOC processes) that give an indication on the behavior of each site in order to explain the differences observed between both sites of the peatland.

This means that the observed changes at the single rewetted site provide a small data set only, so that it remains somehow speculative if the shown changes and effects are specific for rewetting sites. A larger data set which shows the general variability of WTD, DOM quality and DOC export at the selected peatland compared to the specific rewetted site would convince me that the chosen approach is of advantage compared to the one using the stream discharge approach.

Unfortunately we don't have the dataset as asked by the reviewer with in the same point WTD and DOC values. However it is clear that we have two locations with different water table and DOC dynamics, and that the model is able to explain these differences by differences in the partition between slow and rapid drainage. We will discuss this in the revised version of the ms by explaining that the different dynamics in the rewetted area is the most likely due to the restoration because microtopography and vegetation cover are very similar for both site (so no effect on peat properties) and also ponded area were observed after the restauration took place. P11 L4-9

The main reason of using a water table based model instead of a discharge based model is that it can be challenging to monitor discharge in peatlands (flat areas with many outlets varying in time and space). Using a water table based model allows to simulate hydrology when discharge data are missing as it is the case in our study site. Discharge based model would be more robust when simulating fluxes but water table based model has one advantage as it allows the application of the

model in different locations within the same peatland. Therefore the use of a water table based model has to be seen as an alternative to the discharge based model when discharge data are not available.

I suggest that the authors discuss this in more detail including effects of spatial varying redox conditions (also hummocks and hollows), plant cover (what means Sphagnum dominated in this context), mineral redox barriers esp. iron-oxides; which are important for DOC dynamics in fens (is this site minerothrophic or ombrothrophic?).

In this study we mainly focus on the impact of hydrology on DOC dynamics therefore other factors such as redox are not discussed but their potential effects will be added in the new version of the ms. The plant cover is very homogeneous all over the site with a mixture of Graminoids (Mainly Molinia caerulea and in a much lower extent Eriophorum angustifolium and Ryhchospora alba), ericaceous shrubs (Erica tetralix and Calluna vulgaris) and sphagnum species. In addition, the site is an oligotrophic fen that has not developed any abundant hummock and hollow microtopography, such as in a typical ombrotrophic site

Specific comments:

- Please check if all abbreviations are explained when mentioned the first time

Done.

- P3 mention trophic state of fen

It's oligotrophic. It will be added. P3 L28

- P6 L20, . . . the higher the soil moisture, the more DOC is produced . . . . I doubt this very general statement. Permanent water logging reduces DOC production (anaerobic conditions).

This statement was removed.

- P6 L 26 . . . What is DOC loss here, mineralization or export from the peatland or both?

Here, DOC loss corresponds to mineralization and sorption, it was add in the ms. P7 L4

- P6 L32 . . . what is the DOC concentration in rain water?

DOC concentration in the rain was measured in rain water samples and is 2 mg/L

- P7 L 5 expand on how exactly the DOC model was calibrated

The new calibration of the model is explained in detail in the section 2.2.4

- P7 L11 the period . . . was not simulated . . . . because exceptionally high rainfall . . . . Water coming from flooded rivers. I think it is probably a major weakness that the model cannot simulate heavy rain events because those are very important for DOC concentrations and release (connecting pools etc.) please comment on this how this affects the overall quality of the model.

The model is water balance model, it is therefore impossible to account for water coming from exceptional flood events. One have to keep in mind that we speak about very exceptional events (return period of about 50 years). Regular flood events can be simulated by the model. Moreover, the exceptional flood affected only Sr reservoir because peat profile was already fully saturated with rain water when the flood occurred. Therefore the impact of the flood on peat water DOC should be very low. P7 L23-26

See also P8 L28 . . . decrease in model efficiency . . . . explained by exceptional events. Please explain why you think how the model is still useful if it cannot simulate rain/drought events and related preconditions.

This was indeed a weakness of the model. However, following the comments and suggestions of the 2nd reviewer we were able to improve significantly the model calibration. And the model is now able to simulate with the same efficiency wet and dry condition (except exceptional rainfall events as discussed above). 2.2.4 for the calibration and 3.2 for the results

- Please avoid "good results", "satisfactory results" etc. as these are undefined terms or define what this means.

We removed these undefined terms and present only the value of the efficiency criteria.

- P10 L27 and Figure 5, what are upstream and downstream locations? This is discussed on page 10, but I could not find a description in the methods section.

Upstream is control and downstream is rewetted, we made changes.

- Fig. 6 difference in DOC variation between control and rewetted site and discussion on page 9. I think this observation needs further discussion. I don't understand why DOC export (I would prefer "release" here) is episodic at the rewetted site and I don't understand why this observation is consistent with the observation of Birkel et al., 2017 who used a stream discharge approach. Please explain!

DOC release at the rewetted site is episodic because it is linked to the hydrology which is controlled mostly by rapid drainage resulting from rain events. On the opposite DOC release in control site is more controlled by slow drainage and is therefore less impacted by rain events. The observation is consistent with Birkel et al (2017) that found an episodic release of DOC (60% of release in 30% of the time). This is an analysis of the model results and is independent of the use of a water table or a discharge based model (both models simulate DOC release).

- Regarding a detailed explanation of the biogeochemical module, the authors refer to a previous paper. I think the authors should expand a little bit on this especially how draining and rewetting alters the quality of organic matter in comparison to the control site (density etc.). I also wonder why the authors believe that deeper peat is more aromatic. Please explain and include appropriate reference.

The quality of the DOM is not simulated in the model. However, fluorescence analysis shows differences in DOM quality. We can relate this to the hydrology of each site (control by the water table level drawdown) and therefore it is included in the model (DOC model is linked to hydrological

model through water table level). We believe that DOM will be more aromatic in deep layer because it is "older" than in surface where the input of fresh organic matter would lead to less aromatic DOM as discussed in Strack et al (2015).

- I suggest a language polishing by a native English speaker

Done

References:

Birkel, C., Broder, T. and Biester, H.: Nonlinear and threshold-dominated runoff generation controls DOC export in a small peat catchment, J. Geophys. Res. Biogeosciences, 122(3), 498–513, doi:10.1002/2016JG003621, 2017.

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Lessels, J. S., Tetzlaff, D., Carey, S. K., Smith, P. and Soulsby, C.: A coupled hydrology–biogeochemistry model to simulate dissolved organic carbon exports from a permafrost-influenced catchment, Hydrol. Process., 29(26), 5383–5396, doi:10.1002/hyp.10566, 2015.

Strack, M., Zuback, Y., McCarter, C. and Price, J.: Changes in dissolved organic carbon quality in soils and discharge 10years after peatland restoration, J. Hydrol., 527, 345–354, doi:10.1016/j.jhydrol.2015.04.061, 2015.

Wallage, Z. E., Holden, J. and McDonald, A. T.: Drain blocking: an effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland., Sci. Total Environ., 367(2-3), 811–21, doi:10.1016/j.scitotenv.2006.02.010, 2006.

Answer to the review by Dr Bechtold

We thank Dr Bechtold for the thoughtful review of the paper. We agree with all the points raised and we believe we can address them all in order to improve the quality of the paper. We explain below how we plan to address each of them in details.

Review of manuscript "Hydrological control of dissolved organic carbon dynamics in a rehabilitated Sphagnum–dominated peatland: a water-table based modelling approach" submitted to HESS by Bernard-Jannin et al.

The paper deals with the effect of peatland rewetting/restoration on DOC dynamics. The study combines field monitoring (DOC pore water concentrations [DOC] and water table depth) with hydro-biogeochemical modeling. Two monitoring sites were installed within the same acidic fen peatland, one defines the control site (disturbed, drier conditions) and one the rewetted case due to recent (3 years) blocking of a ditch. Field data indicate a strong effect of the rewetting on the water table depth (>20 cm shallower water levels during summer) and higher [DOC] in summer in the rewetted location compared to the control. Also the quality of DOC seems to change due to rewetting. Modeling results indicate very contrasting fluxes at the two sites, fast runoff with very low evapotranspiration at rewetted sites vs. slow "deep" drainage at control site, which is interpreted to control DOC composition and export.

The basic scope of the paper (topic, field data, model approach) is interesting, relevant for the community and suitable for publication in HESS. The authors dealt with a challenging site because fluxes were not observed. Calibration of a hydrological model only on water table depth data with the objective to interpret resulting fluxes is questionable although maybe not impossible when setting sufficient constraints on calibration scheme and parameters, and when providing reliable uncertainty estimates. However, as the modeling, and in particular the calibration, has been conducted and presented now, one cannot trust the highly questionable simulated hydrological fluxes (e.g. extremely low ET at rewetted site). Fluxes are crucial for the [DOC] dynamics, e.g. ET causes a 'physical' accumulation of DOC in the pore water, thus one can also not rely on the following implications for DOC concentrations and exports. In my major points, I thus focus on the hydrological part of the paper. The DOC part is commented with less detail, although it must be also fundamentally revised because I assume that results will change considerably with an update of the hydrological modeling.

In general, as mentioned before, fluxes of a hydrological model calibrated only on water table depth should be interpreted carefully. I present my major concerns and give some additional recommendations afterwards.

Major points

I see several major problems in the hydrological modeling part of the study. The hydrological model is of fundamental importance for the results of the manuscript. The authors intent "to identify the main hydrological processes and factors controlling DOC dynamics" with their model which is based

on a conceptual approach based on reservoirs. Modeled are two monitoring sites that lie in the same disturbed fen peatland. I assume the two sites were very similar before 2014 (same vegetation, 60 cm peat thickness, … same peat properties?). The only that changed in 2014 was the boundary condition for the rewetted site, which is effectively a higher drainage level due to ditch blocking.

Separation into boundary-condition dependent and boundary-condition independent parameters:

Having repeated the field situation, it is only possible to rely on the simulated fluxes when all model parameters that do not depend on changed boundary conditions (i.e. here the changed drainage level) are the same for both monitoring sites. As far as I understood the three discharge coefficients (overland, lateral runoff through peat, and "deep" drainage) are dependent on the raised drainage level due to ditch blocking. As the conceptual model does not include a drainage level as a boundary condition, these parameters have to be tuned that simulated water levels match observed ones. (*This is actually a major weakness of the presented conceptual model, as for a more process-type of model only a single boundary condition would need to be changed and/or calibrated if not known precisely. Emphasize this disadvantage.*)

It is true that only one boundary condition would need to be changed for a process-type model, but additional(s) parameter(s) would be required to describe the process. Process-type models at the interface between surface and peat waters, including exchange between these two compartments could be complex and difficult to calibrate. The idea to use a more conceptual model is to have a model with few input parameters needed (at the cost of increase number of calibrated parameter indeed). This disadvantage of conceptual model over process based model will be stated in the ms. P2 L25

In contrast to the three discharge coefs, I consider the ET crop coefficients and infiltration rate from the peat-macro to the peat-matrix reservoir (Imax) as "boundary-condition independent". They should be thus calibrated to the same value for both sites. In the study, however, all these parameters were calibrated separately at both sites resulting in extreme differences for the crop coefficients and Imax at the two sites. As a consequence, e.g. ET is extremely low at the rewetted site. The authors recognized that this flux is unphysical and explain it by additional open water reservoirs (not modelled) that are laterally coupled to the modeled 1D profile and buffer water table depth dynamics during high water levels. I think this might be an important process and a valid interpretation, but a dramatic reduction of ET for the rewetted site is an unacceptable result for the scope of the paper. If this process (open water storage) is really relevant, it needs to be accounted for. To further prevent such an "overfitting effect", I recommend that authors think about reliable constraints during the calibration. For example, I suggest to calibrate all parameters simultaneously for both sites keeping the "system boundary condition independent" parameters the same for both sites ('multi'-site calibration approach).

We agree with the comments of Dr Bechtold and redid the calibration by keeping ET and Imax coefficients similar for both sites in order to perform a multi-site calibration. In addition we decided to improve the choice of the calibration period by using 2014 and 2017 that are the driest and wettest years. 2015 is now used as a validation. In addition, we present additional efficiency criteria to assess the quality of the model (br² and RMSE). The new calibrated parameters are presented below (table 1, Fig. 1). We constrained the ET coefficients values to be in a range in agreement with observed values (Lafleur et al., 2005). The objective function is now the sum of NS for the two

locations (control and rewetted) and two validation periods (2014 and 2017). We can see from the results that, despite being less performing than in the first version of the paper, the model is still able to reproduce water table for both site when taking into account a multi site calibration approach, with little differences in the coefficients found in the first version of the ms (except for evapotranspiration downstream). NS coefficients are all positives; br2 all greater than 0.2 and RMSE are between 1 and 9 cm. The model performed better for the control site in the dry year than in the wet year and the opposite can be observed for the rewetted site. Finally, we don't observe a drop of performance of the model for the validation period. See section 2.2.4 for the method and 3.2 for results.

Table 1: Updated calibrated parameters and performance criteria based on a multi-site calibration approach. Range of parameters calibration are also indicated)

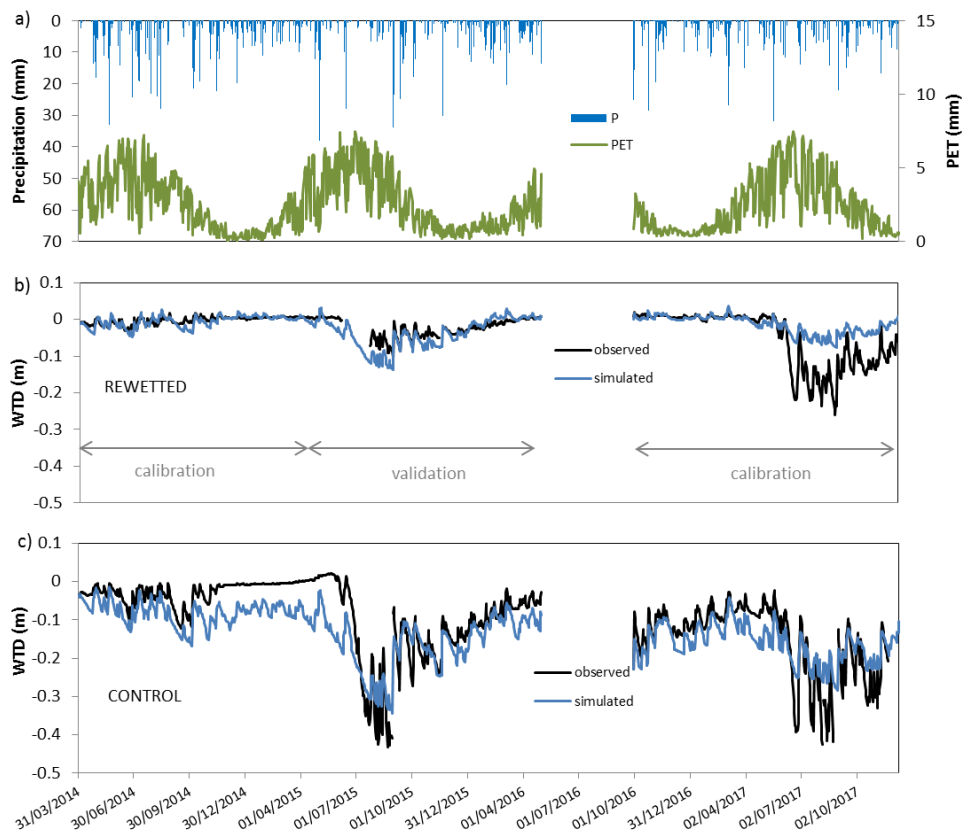|	Rewetted	Control	Range
Kcd	0.37	0.37	$0.01 - 0.5$
Kcg	0.40	0.40	$0.4 - 0.8$
Imax	0.84	0.84	$0.2 - 5$
αp	1.6E-05	1.9E-03	$0 - 0.01$
αr	0.20	0.37	$0 - 0.5$
αsr	0.20	0.27	$0 - 0.5$
Calibration (2014/15)			
NS	0.10	0.61	
Br2	0.52	0.67	
RMSE (m)	0.01	0.01	
Calibration (2016/17)			
NS	0.25	0.16	
Br2	0.26	0.24	
RMSE (m)	0.065	0.080	
Validation (2015/16)			
NS	0.10	0.30	
Br2	0.54	0.39	
RMSE (m)	0.02	0.09	

Figure 1: (a) Time series of meteorological data (PET, potential evapotranspiration and P, precipitation) used as input data in the hydrological model, **(b)** simulated and observed WTD in the rewetted site and **(c)** simulated and observed WTD in the control site. Calibration and validation periods are also indicated.

Reliability of validation period:

Validation with independent data is crucial. The authors used the third year of data for validation. This is basically ok. However, Nash-Sutcliffe efficiency (NS) drops from 0.8 (calib) to 0.3 (valid) for one of the sites. The enormous drop of performance is a strong indication of overfitting. Authors argue that it might be related to the exceptional flooding event between the second and the third year. If they are convinced that this is the reason, then the whole validation period is useless because we learn nothing about the reliability of the calibrated model from it. In fact, from what I can read and see in the paper, I have the impression that the third year can be used for validating the hydrology, because the initial water table depth of the validation period seems to be quite consistent between model and data. Or were the initial condition of the model set to the observed data? If yes this must be stated clearly, and the validation period should be shortened as validation NS would be overestimated by this manual adjustment of the state variable.

As stated in the previous point, we modify calibration and validation period. Calibration is performed on the driest and the wettest year (2014 and 2017) and validation is perfomed on an intermediate year (2016). For the simulation of 2017, the starting H is set as the observation, this will be made clear in the ms. With the new calibration strategy (multi sites) and the change of calibration/validation periods we don't observe a drop of performance between calibration and validation.

Definition of reservoirs

Sm is 0 at the lower peat boundary, why? Did authors determine in the lab that there are no macro-pores at 80 cm? At the surface the total porosity (Sm+Se) of the peat is defined to be 1. Justify also this decision, as it is not obvious how a material can have a porosity of 1. Did authors want to prevent a discontinuity between soil and surface storage? But why

The conceptual model was build in a way to obtain a good compromise between the number of parameters needed (2 parameters, Hmax and Θinf) and a solid description of the flows at the interface between soil and surface. Sm reservoir was conceptualized to be a transitional reservoir between 100% Se peat at the lower boundary and a 100% Sr surface at the upper boundary. We thus made the following assumptions: macroporosity is null at the bottom of the peat layer and the total porosity is one at the surface, which is in agreement with observed values (Bourgault et al., 2017).

DOC measurements

The definition of the reservoirs is of particular importance also for the DOC interpretation. Were the sampling pipes emptied before taking samples? If not, it is not clear what the [DOC] in the pipes actually is (mixture of recent rain water, [DOC] of soil pore water X days/weeks before sampling minux the losses due to being 'open water' in the pipe afterwards, etc.) . If yes, mainly the macro-pore water was refilling the empty pipe afterwards, i.e. authors need to compare the field data with modeled Sm [DOC], if I understood the approach correctly. Regarding the issue of sampling different soil pore spaces see also Zsolnay, 2003, Dissolved organic matter: artefacts, definitions, and functions, Geoderma.

Indeed, the sampling pipes were emptied before sampling, so we can assume that we measure mainly [DOC] in Sm. We propose to calibrate production and loss constant on [DOC] in Sm. New results are shown in Fig 2. The model still perform well for after the changes except fot the year 2017 in control were concentration are systematically over estimated. This can be related to the difficulties of the model to simulate water table for this period. However the model simulated lower concentrations in rewetted than in control as observed. Calibrated parameters (only 2 parameters now as only DOC in Sm is simulated) and efficiency criteria are shown in table 2. Despite a relatively high RMSE, the model is able to represent the trend for most of the simulated periods. This is in agreement with the fact that hydrology plays a key role in controlling [DOC] dynamics through the water table depth as stated in the first version of the ms. Changes were made in data collection (P4 L6-11), figure and table were updated.
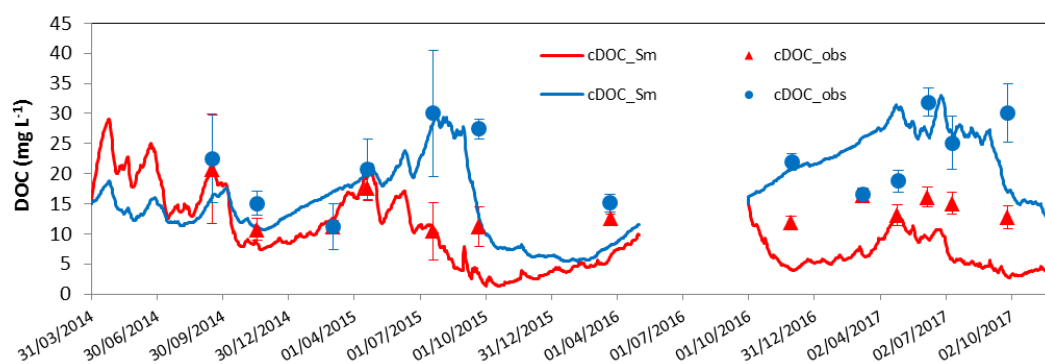

Figure 2: Simulated [DOC] in Sm and observed [DOC] after new calibration

Table 2: Calibrated parameter and efficiency criteria of the DOC model

	Rewetted	Control
kprod	5.0E-08	9.0E-07
kloss	5.0E-04	1.2E-02
Calibration (2014/15)		
RMSE (mg.L^{-1})	5.4	1.6
Br2	0.003	0.89
Calibration (2016/17)		
RMSE (mg.L^{-1})	8.6	8
Br2	0.18	0.03
Validation (2015/16)		
RMSE (mg.L^{-1})	8.9	10.8
Br2	0.34	0.31

Effect of flooding event on DOC validation period

What is the [DOC] in the river water? And do authors have any knowledge about how the flooding event affected the [DOC] of the peat profile in the third year? Authors need to discuss this. Till now, the third year is in particular questionable for validating the DOC model.

The DOC from the river during the flood was measured and is equal to 12 mg.L^{-1}. We think that this 50 years return period flood affected only Sr reservoir because the peat profile was already fully saturated with rain water when the flood reached the peatland. Therefore the impact of the flood on peat water and on DOC is expected to be negligible. P7 L24-26

Recommendations:

Authors must establish much more confidence for their model. Besides taking into account my major and minor comments, I recommend that authors elaborate a sophisticated uncertainty analysis that provides uncertainty estimates for the flux components, i.e. that shows how variable the predicted flux components are for similarly performing models (similar fits of water table depth). Use probabilistic approaches like e.g. Bayesian modeling or GLUE. Authors can only generate sufficient confidence into the model results when authors are very critical with the calibration. For that, consider also the effect of optimizing the parameters for different objective functions, not just the daily NS or RMSE (e.g. different levels of aggregating the time series, daily, weekly, monthly averages) and add plausible errors to the forcing and water table depth data. These are ideas for directions authors need to look for.

Following the recommendations of Dr Bechtold, we performed an uncertainty analysis to better assess the confidence of the simulated fluxes. We ran a GLUE analysis with 50 000 runs using a

criteria of NS>0 for both locations to select behavioral simulations. The ranges of each parameters used in the analysis are the same than in table 1. 5th and 95th percentiles of each fluxes are presented in table 3.

Table 3: 10th and 90th percentiles of the fluxes resulting for the GLUE analysis (50 000 runs, behavorial runs for NS>0 for both sites). Best fit is indicated and 5th and 95th percentiles of the behavioural runs are between bracket.

	Rewetted (5th – 95th)	Control (5^h – 5^h)
P (mm yr^{-1})	787	787
ET (mm yr^{-1})	357 (284 – 374)	357 (284 – 374)
Q (mm yr^{-1})	417 (399 – 489)	466 (370 – 494)
O (mm yr^{-1})	233(188 – 394)	3.6 (0 – 40)
R (mm yr^{-1})	183 (42 – 220)	352 (20 – 355)
D (mm yr^{-1})	2 (1 – 79)	111 (102 – 444)

Uncertainty on fluxes is high (as we can expect from the use of a conceptual model) but we can see significant differences concerning the partition between drainage and overland flow for the two locations (slow deep drainage dominated upstream and rapid surface drainage dominated downstream). These findings are in agreement with results presented in the first version of the ms. We included the method (2.2.4) and the results of the uncertainty analysis (3.2).

All the changes on the hydrological model calibration have been transfer to the DOC model as discussed above. The DOC balance has been recalculated including uncertainty analysis results (table 4). Results and discussion parts will be modified according to the new findings.

Table 4: DOC release for control and rewetted location over the studied period. Best indicates values for the best set of parameters. 10th and 90th percentiles resulting of the uncertainty analysis are also indicated.

	Rewetted (5th – 95th)	Control (5^h – 5^h)
DOC exports total (g C m^{-2} yr^{-1})	3.6 (3.5 – 7.2)	8.6(8.5.7– 25.5)
DOC exports Se (g C m^{-2} yr^{-1})	0.1 (0.1 – 3.6)	3.8 (3.8 – 14.3)
DOC exports Sm (g C m^{-2} yr^{-1})	3.5(3.1 – 3.6)	4.8(0.9– 11.5)

Minor comments:

Page 4 - L15: "identify the locations" – I do not understand the sentence.

It was cahnged: "Tukey's post hoc tests were used to identify the significant differences" P4 L26

Page 5 – L4: What is Smax? Not defined after the equation but two paragraphs later.

Done P5 L15-16

Page 6 – L32: Why t+1 for PDOC and LDOC? Isn't it dependent on the concentration of time step t. Clarify this also in eqs 7 and 8

This was a mistake in writing the equations. Produced and consumed DOC are indeed dependent on time step t.

Page 7 – L14: How can the maximum porosity of the peat layer be equal to 1?

The maximum porosity represents the porosity at the surface, which is one.

Page 7 – L14: "flooded river" … wording. The river itself cannot be flooded

Changed to : "the water coming from the river during floods" P7 L24.

Page 7 – L20: Give both NS and RMSE for both the hydrological and the DOC model. Not clear why different skill metrics have been chosen for the two variables. Would be interesting to know NS of the DOC model. It seems to be barely better than just the mean of the observed concentrations (i.e. NS~0), in particular for the validation period.

The reason we didn't add the NS for the DOC is that NS is especially relevant when considering continuous time series with high variation (peaks in discharge or water table data). As we don't have many DOC measurements and the variations is not as high as for water table data, we think that NS is not relevant to correctly describe the efficiency of the DOC model and that is why we just presented the RMSE that give quantitative information on the model performance. It is not unusual to not present NS when quality data are scarce, e.g. Garneau et al. (2017). We propose to present NS, Br2 and RMSE for the hydrology and RMSE and Br2 for the DOC model.

Page 7 – L22: calibrated over the calibrated hydrol. model. …. improve wording.

Changed to:"the DOC module was calibrated after the calibration of the hydrological model" P8 L12-13

Table 1: correct table, reservoirs and discharge description are confused !

We improved the description of discharge and reservoirs.

Table 1: How can Imax as a rate have the unit [mm]? A rate is always per time. Table 2: Format table correctly. Michel Bechtold, KU Leuven, BE; 6th Dec 2017.

This will be change. Imax is defined in mm in the original paper. The time unit was implicit and corresponds to the model time step. It will be change to $mm.day^{-1}$ (as the model uses a daily time step).

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Hydrological control of dissolved organic carbon dynamics in a rehabilitated *Sphagnum*–dominated peatland: a water-table based modelling approach

Léonard Bernard-Jannin[1,2,3], Stéphane Binet[1,2,3,4], Sébastien Gogo[1,2,3], Fabien Leroy[1,2,3], Christian Défarge[1,2,3,5], Nevila Jozja[5], Renata Zocatelli[5], Laurent Perdereau[1,2,3], Fatima Laggoun-Défarge[1,2,3]

[1]Université d'Orléans, ISTO, UMR 7327, 45071, Orléans, France
[2]CNRS, ISTO, UMR 7327, 45071, Orléans, France
[3]BRGM, ISTO, UMR 7327, 45071, Orléans, France
[4]ECOLAB, Université de Toulouse, CNRS, UPS, INPT – UMR 5245, Toulouse, France
[5]CETRAHE, Université d'Orléans, 45072, Orléans, France

Correspondence to: Léonard Bernard-Jannin (l.bernardjannin@gmail.com)

Abstract

Hydrological disturbances could increase dissolved organic carbon (DOC) exports through changes in runoff and leaching, reducing the potential carbon sink function of peatlands. The objective of this study was to assess the impact of hydrological restoration on hydrological processes and DOC dynamics in a rehabilitated *Sphagnum*–dominated peatland. A conceptual hydrological model calibrated on the water table and coupled with a biogeochemical module was applied to La Guette peatland (France), which experienced a rewetting action on February 2014. The model (eight calibrated parameters) reproduced water table($0.1 < NS < 0.61$) and pore water DOC concentration ($2 < RMSE < 11$ mg L^{-1}) time series (01/04/2014 to 15/12/2017) in two contrasted locations (rewetted and control) of the peatland. Hydrological restoration was found to impact the water balance through a decrease in slow deep drainage and an increase in fast superficial runoff. Observed DOC concentrations were higher in summer in the rewetted location compared to the control area and were linked with a difference in dissolved organic matter composition analyzed by fluorescence. Hydrological conditions, especially the severity of the water table drawdown in summer, were identified as the major factor controlling DOC concentration dynamics. The results of the simulation suggest that the hydrological restoration did not affect DOC loads, at least on a short-term period (3 years). However, it impacted the temporal dynamics of DOC exports, which were the most episodic and mainly transported through fast surface runoff in the area affected by the restoration while slow deep drainage dominated DOC exports in the control area. In relation with dominant hydrological processes, exported DOC is expected to be derived from more recent organic matter in the top peat layer in the rewetted area than in the control area. Since it is calibrated on water table and DOC concentration, the model presented in this study proved to be a relevant tool to identify the main hydrological processes and factors controlling DOC dynamics in different areas of the same peatland. It is also a suitable alternative to a discharge calibrated catchment model when the outlet is not easy to identify or to monitor.

1 Introduction

Sphagnum–dominated peatlands represent a major stock of the global soil carbon (C) pool (Gorham, 1991). Dissolved organic carbon (DOC) exports through runoff and leaching could account for up to 25% of the C fluxes (Yu, 2012), reducing the potential C storage function of peatlands (Billett et al., 2004) and impacting downstream water quality (Ritson et al., 2014). DOC dynamics in peatlands has been found to be strongly controlled by site hydrology, especially by the water table depth (WTD) (e.g. Hribljan et al., 2014; Jager et al., 2009; Strack et al., 2008, 2015). Therefore, hydrological disturbances such as drainage can lead to increased DOC exports in relation with WTD variations (Strack et al., 2008; Worrall et al., 2007). Where disturbances have occurred, hydrological restoration can be undertaken to reestablish peatland functioning (Menberu et al., 2016), with a potential impact on DOC dynamics and exports (Glatzel et al., 2003; Strack et al., 2015; Worrall et al., 2007).

In peatlands, as in many terrestrial ecosystems, DOC dynamics is controlled on the one hand, by its production to consumption ratio in pore water, and, on the other hand, by lateral water fluxes that drive its exports. DOC production through organic matter decomposition is known to increase with temperature (Clark et al., 2009; Freeman et al., 2001) and DOC consumption, mainly due to heterotrophic bacterial activity, is also positively correlated to temperature and can lead to decreased DOC concentrations during drought (Clark et al., 2009; Pastor et al., 2003). The export of the DOC produced in pore water is mainly controlled by peatland hydrology (Pastor et al., 2003; Strack et al., 2008), especially by the partitioning between quick near surface flow and groundwater flow (Birkel et al., 2014). Due to the complexity of the interactions between these factors, field studies can show contradictory results on the effect of rewetting on DOC dynamics, with some studies reporting increasing concentrations (Hribljan et al., 2014; Strack et al., 2015) while others report decreasing concentrations (Höll et al., 2009; Wallage et al., 2006).

While changes in DOC net production resulting from WTD drawdown can be assessed through field monitoring, the relative contributions of DOC production and consumption cannot be evaluated (Strack et al., 2008). Process-based biogeochemical models can be relevant tools to understand DOC dynamics (Evans et al., 2005) and can help to identify factors controlling its production and consumption in such environments. In particular, conceptual models are appropriate because, despite requiring a calibration phase to adjust parameters (unlike in more physically based models), they are parsimonious in terms of their number of parameters, avoiding overparametrization issues (Birkel et al., 2017; Seibert et al., 2009). Another advantage of using conceptual models is that they usually require commonly measured data (e.g. precipitation and water discharge or water level) so they can be applied to numerous study sites where such data are available, making them a suitable tool to compare sites with different settings.

When studying DOC dynamics in peatlands, existing conceptual models are composed of a DOC module combined with a hydrological model (Birkel et al., 2014; Futter et al., 2007; Lessels et al., 2015). In these studies, the hydrological model is usually adapted to the catchment and calibrated on stream discharge. However, stream discharge in peatlands is difficult to monitor because the diffuse runoff that occurs in these flat areas can result in multiple outlets. Furthermore, while WTD is a

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key parameter to explain DOC dynamics (Strack et al., 2008), it is usually not considered for calibration, and water discharge is preferred instead. Therefore, while these models have proven to be well adapted when modelling a catchment containing a peatland area (Birkel et al., 2014; Futter et al., 2007; Lessels et al., 2015), where the outlet is well defined, they are more difficult to apply when considering a peatland alone. In this case, the model should focus on the simulation of the

5   WTD, especially when studying DOC dynamics in peatland pore water. Furthermore, a model based on WTD can also provide interesting information about the spatial variability of the dominant hydrological processes when applied to different locations within the same peatland. Models simulating DOC dynamics are usually based on a simple mass balance and DOC production and consumption rates, usually expressed as first order rate processes (Birkel et al., 2014; Futter et al., 2007; Lessels et al., 2015). In these cases, DOC production and consumption rates are modified using terms related to temperature

10   and soil moisture as these two parameters control the microbial activity and peat decomposition that regulate the production and consumption of DOC in peat water.

In this study, we propose to couple an existing WTD dependent hydrological model specially developed for simulating peatland hydrology (Binet et al., 2013) with a biogeochemical module simulating DOC production and consumption as first order rate processes. The hydrological model was calibrated on WTD, which is an important driver of the DOC dynamics in

15   peatland. The model was applied to two sites of a *Sphagnum*-dominated peatland, one of them having experienced a rewetting action. The objectives of this study were 1) to identify the dominant hydrological processes in both a rewetted and undisturbed peatland locations, 2) to understand how these hydrological processes affect the DOC dynamics in each of these two locations, and 3) to assess the impact of the rewetting on DOC export in a *Sphagnum*-dominated peatland.

2 Material and methods

20   ### 2.1 Study area and data collection

2.1.1 Site description

The La Guette peatland (150 m.a.s.l., 47°19N, 2°16'E, 20 ha), located in the Sologne forest (Neuvy-sur-Barangeon, France) is an acidic fen with a homogeneous plant cover mainly composed of moss patches (*Sphagnum cuspidatum*, *S. rubellum* and *S. palustre*), and ericaceous shrubs (*Calluna vulgaris* and *Erica tetralix)*. The peatland has been invaded by *Molinia caerulea*

25   and *Betula spp* for 70 years with an acceleration of the invasion in recent decades (Gogo et al., 2011). This was partly caused by a road ditch located near the outlet that accelerated the peatland drainage (Fig. 1). In February 2014, hydrological restoration was undertaken in the road ditch to raise the WTD and reduce its fluctuations in order to promote soil rewetting. The site is an oligotrophic fen that has not developed any abundant hummock and hollow microtopography, such as is found in a typical ombrotrophic site.

2.1.2 Data collection and analysis

WTD and DOC concentrations ([DOC]) in pore-water were monitored in two locations of the peatland. One is affected by the restoration work and is called "rewetted" while the other is not and is called "control" (Fig. 1). WTD were recorded in piezometers since February 2014 at a 15 min time step using vented-pressure probes (Orpheus mini, OTT Hydromet). Pore-
5 water was sampled in 4 wells surrounding each piezometer (each of them less than 5m from the piezometer) during 13 campaigns that took place every 1 to 4 months between February 2014 and December 2017. The pipes were emptied before sampling to avoid the presence of rain water and ensure that the water sampled was representative of the peatland water. The water samples were filtered using 0.45 µm PES filters on the field and transported in an ice box to the lab where DOC concentrations were determined with a TOC analyzer (TOC-L, Shimadzu) within 2 days following sampling (samples stored
10 at 4°C). In this study, the measured [DOC] is considered to correspond to [DOC] of the macropore water as pipes are expected to be filled by gravitational water after being emptied (Zsolnay, 2003) .

Pore-water dissolved organic matter (DOM) was characterized by its fluorescence properties through three-dimensional excitation emission matrices (EEMs; Fellman et al., 2010) acquired with F-2500 and F-7000 spectrofluorometers (Hitachi). EEMs were recorded using a 10 x 10 mm quartz mirrored cell, at a photomultiplier voltage of 400 V, with a scan speed of
15 1500 nm/min, over ranges of excitation of 220–500 nm, in 10 nm steps, and emission of 230–550 nm, in 1 nm steps, respectively; the slit widths of both monochromators were set at 5 nm. A parallel factor analysis (PARAFAC) was performed using the drEEM toolbox according to the processing described in Murphy et al. (2013). The method was applied to analyze the samples of two campaigns, those of March 2015 (wet conditions) and September 2015 (dry conditions) in order to compare DOM composition for two contrasted hydrological settings.
20 Meteorological data were recorded at an hourly time step from a station located within the peatland between the two studied areas (Fig. 1). Rainfall was measured with a tipping bucket rain gauge and potential evapotranspiration (PET) computed with the FAO Penman-Monteith equation at an hourly time step (Allen et al., 1998) using local solar radiation, wind speed, relative humidity and temperature measurements.

The effect of hydrological conditions (dry period from 1st of June to 30th of November and wet period from 1st of December
25 to 31st of May) and location (rewetted or control) on [DOC] and DOM composition were tested using two-way ANOVA and Tukey's *post hoc* tests were used to identify the significant differences.

2.2 Model description

The modeling approach used in this study combines a conceptual hydrological model with a biogeochemical model simulating DOC dynamics. The hydrological model is based on a conceptual water table dependent hydrological model that
30 has already been successfully applied in the study area (Binet et al., 2013). This model is coupled with a module based on functions describing DOC production and consumption in pore-water which was developed for this study. The model is described in detail in the following sub sections.

2.2.1 Hydrological model

The hydrological model is based on the model described by Binet et al. (2013). It is a daily time step, reservoir model specifically developed for peatland hydrology integrating a WTD dependent runoff. Compared to the original model, a few modifications were made in this study in order to improve the model. The overall structure of the new model is presented in Fig. 2.

The relation between soil water content and WTD was improved. In the original version the user had to know the relation between WTD and soil water content. Now the model automatically computes the soil water content based on the porosity of the percolation reservoir (Θmin), the porosity at the surface (Θmax), and peat depth (Hmax) (Fig. 2). The porosity of the percolation reservoir is considered to be constant over the depth and equal to Θmin. The porosity of the Sm reservoir is equal to 0 at the maximum depth (Hmax) and increases linearly with the storage until the surface where it reaches Θmax-Θmin, Θmax being the total porosity of the Se and Sm reservoirs at the surface. The new relation between WTD and soil moisture content is given by

$$H(\theta) = \frac{\ln(\theta/\theta min)}{\left(\frac{\theta max - \theta min}{Smax}\right)} \tag{1}$$

$$Smax = \frac{Hmax\,(\theta max - \theta min)}{\ln(\theta max/\theta min)} \tag{2}$$

where H is the WTD (mm), Θ is the sum of the porosities in Sm and Se at a given H and ==Smax is the maximum amount of water contained in both Sm and Se (mm).==

With this modification, the maximum amount of water stored in the Se reservoir (Semax in mm), which was a calibrated parameter in the original version of the model, is now automatically computed with

$$Semax = \theta \min Hmax \tag{3}$$

Overall, this definition improved the relation between WTD and the water content. In the original version of the model, the porosity of the Sm reservoir was equal to 1, while it now depends on the WTD, to better represent reality (Bourgault et al., 2017).

A third reservoir was added, Sr (overland flow storage), in order to differentiate the overland flow water (Sr) from the water entering the peat macroporosity (Sm), which were not differentiated in the original model. While it might not significantly affect the hydrological model, this was done to prepare for the addition of biogeochemical processes which are different for these two reservoirs. Following the addition of the Sr reservoir, a maximum amount of water contained in the Sm reservoir is defined (Smmax in mm) and is computed according to

$$Smmax = Smax - Semax \tag{4}$$

The routing was also slightly modified to take into account the addition of the new reservoir (Sr). Water from precipitation first fills the Sm reservoir, and the Sr reservoir starts to be filled only when Sm is full (Sm=Smmax). The order of priority in which evapotranspiration is removed from the 3 reservoirs is now Sr, Sm and Se.

Finally a discharge coefficient was added to compute the flow from the new Sr reservoir,

$$O = \alpha o\, Sr \tag{5}$$

where O is the overland flow from the Sr reservoir (mm), αo is the discharge coefficient of the Sr reservoir (-) and Sr is the volume of water in the Sr reservoir (mm).

This flux is added to the total discharge which is now computed according to

$$5 \quad Q = D + R + O \tag{6}$$

where Q is the total discharge (mm), D is the percolation rate from the Se reservoir (mm) and R is the runoff rate from the Sm reservoir (mm).

Given the structure of the model, D represents the drainage of the retention reservoir and can be assimilated to slow deep drainage. R and O represent the drainage of the macroporosity and the overland flow and can be assimilated to fast

10   superficial drainage.

Concerning evapotranspiration, the crop coefficient used to compute evapotranspiration (ET) from ETP was separated into the dormant (Kcd) and the growing (Kcg) season. The latter runs from May to September with a linear relation between the two coefficients during April and October. This was done to take into account the impact of vascular vegetation growth in peatlands. Finally, a condition was added so that the water level in Sm cannot be lower than the water level in Se.

15   The computation of the following processes remained unchanged: infiltration from Sm to Se (ISe), percolation (P) and runoff (R). The reader is referred to Binet et al. (2013) for a more detailed description of the computation of these processes.

The modified hydrological model is now controlled by 9 parameters (Tab. 1). Three input parameters describing the peat structure (Hmax, Өmin and Өmax) and 6 calibrated parameters controlling water fluxes in the model: Kcd and Kcg for ET, Imax for the ISe, and a discharge coefficient for each reservoir (αp, αr and αo). The forcing variables remained daily

20   precipitation and PET as in the original model.

2.2.2 DOC model

To simulate DOC dynamics, a module was developed based on first order production and loss, and mass balance, similarly to what can be found in the literature (Birkel et al., 2014; Lessels et al., 2015). Production and loss are computed in the Se

25   and Sm reservoirs only since the main biogeochemical processes linked to DOC dynamics occur in soil storage and no reaction takes place in the Sr reservoir. DOC production was based on a production coefficient and two additional modifiers based on soil water content and air temperature, as usually considered in DOC production models (Birkel et al., 2014; Futter et al., 2007; Lessels et al., 2015). The effect of the temperature was based on a Q_{10} formulation (the factor by which the rate of a reaction increases for every 10-degree rise in the temperature) with a value of 2 according to the value commonly used

30   in DOC production models (Lessels et al., 2015; Michalzik et al., 2003; Tjoelker et al., 2001). The rate modifier based on water content was expressed with a quadratic function to represent the non-linear production of DOC with the variation in soil moisture. DOC production is computed as follows:

$$PDOC = k_{prod}\, S\, SOC\, 2^{T/10}\, (S\,/\,Smax\,)^2 \tag{7}$$

where PDOC is the DOC production rate (mg day^{-1} m^{-2}), k_{prod} is the production constant (day^{-1}), SOC is the amount of organic carbon per mm of peat per square meter (mg mm^{-1} m^{-2}), T is the air temperature (°C), S is the amount of water in the reservoir considered (mm) and Smax is the maximum amount of water in the reservoir considered (mm).

DOC loss, <mark>corresponding to mineralization and sorption</mark>, was based on a loss coefficient linked to air temperature in the same way as DOC production. DOC loss is computed according to

$$LDOC = k_{loss} \ [DOC] \ S \ 2^{T/10} \tag{8}$$

where LDOC is the DOC loss rate (mg day^{-1} m^{-2}), k_{loss} is the loss constant (day^{-1}), [DOC] is the DOC concentration in pore water (mg L^{-1}) and S is the amount of water in the reservoir considered (mm).

Finally, the mass balance of DOC is computed in the Sm and Se reservoirs

$$DOC_{Sm}^{t+1} = DOC_{Sm}^t + PDOC_{Sm}^t - LDOC_{Sm}^t + [DOC]_{rain}ISm - [DOC]_{Sm}^t(ISe + R) \tag{9}$$

$$DOC_{Se}^{t+1} = DOC_{Se}^t + PDOC_{Se}^t - LDOC_{Se}^t + [DOC]_{Sm}^tISe - [DOC]_{Se}^tD \tag{10}$$

where the exponent represents the time step, the subscript indicates the reservoir considered (Sm or Se), $[DOC]_{rain}$ is the DOC concentration in rain water (mg L^{-1}), Ise is the infiltration from Sm to Se (mm) and Ism is the infiltration from Sr to Sm (mm).

The DOC model is controlled by 6 parameters (Tab. 1). Two input parameters (SOC and [DOC]$_{rain}$) and two calibrated parameters controlling DOC dynamics (kloss and kprod). The additional forcing variable is air temperature.

2.2.3 Model setup

The hydrological and biogeochemical model parameters were calibrated for each piezometer of the peatland for the <mark>wettest period (01/04/2014 to 01/04/2015) and the driest period (01/10/2016 to 15/12/2017) considering available data. The model was validated over a period with a more intermediate condition (01/04/2015 to 01/04/2016).</mark> The period from 01/05/2016 to 30/09/2016 was not simulated because exceptionally heavy rainfall <mark>(return period of about 50 years)</mark> occurred on 31/05/2016, causing extensive flooding in the whole region. The definition of the model is not suitable for these exceptional events because the water <mark>coming from the river during the flood is not taken into account</mark> in the model. <mark>However, the flood was not expected to impact [DOC] in the peat profile since it was already saturated with rain water when the flood of the river reached the peatland. In addition, it has to be noted that the model is able to represent less exceptional events as long as the flood does not reach the peatland (estimated at a 10 to 20 years return period in our case)</mark>. Θmin and Θmax were set at 0.2 and 1, respectively, and Hmax at 0.6 m, based on field data. $[DOC]_{rain}$ was 2 mg L^{-1} according to measurements performed on rain water and SOC was set at 833 10^3 mg mm^{-1} m^{-2} following measurements performed on peat samples. <mark>Initial conditions were set to observed values for water table depth and to 15 mg L^{-1} for [DOC].</mark>

2.2.4 Model calibration and evaluation

The parameters were calibrated with a Nelder-Mead algorithm (Varadhan et al., 2016) implemented in the R software (R Core Team, 2012) using the Nash-Sutcliffe coefficient (NS, Nash and Sutcliffe, 1970) as the objective function for the hydrological module and the root-mean-square error (RMSE) for the DOC concentrations in Sm. NS was chosen for the

5 hydrological model because it can take the large variation of the water table into account while RMSE was chosen for the DOC model because [DOC] variations are not very large and it provides a quantitative estimate of the error. In addition, the coefficient of determination multiplied by the slope of the regression (Br2, Krause et al., 2005) was computed for both the hydrological and DOC model, to better assess the quality of the simulations. The hydrological model was calibrated following a multi-site strategy. The parameters independent of the location within the peatland were kept similar for both

10 sites (Kcd, Kcg and Imax) and only the parameters expected to differ between sites were set free for each site (αr, αsr and αp). This was done in order to prevent an overfitting of the model. The hydrological module was calibrated first because substantially more water table data were available than DOC concentrations. The DOC module was then calibrated after the calibration of the hydrological model. The ranges allowed for the calibrated parameters are indicated in Tab. 3. A sensitivity analysis was performed using a latin-hypercube one-factor-at-a-time (LHOAT) procedure (Zambrano-Bigiarini and Rojas,

15 2014) implemented in the R software. The sensitivity analysis was based on NS for the hydrological model. The sensitivity analysis was not performed for the DOC model since it contains only 2 parameters, both considered as sensitive. Finally, an uncertainty analysis of the hydrological model was performed based on a GLUE analysis (Beven and Freer, 2001) with 50 000 runs, using a criteria of NS>0 for both locations to select behavioral simulations. Parameters ranges were the same than the one used for the calibration (Table 3). Uncertainty boundaries on fluxes are presented as the 5th and 95th of the fluxes

20 obtained from the weighted behavioral parameter sets. The main objective of the uncertainty analysis was to better assess the confidence in the simulated fluxes for which no data were available.

3 Results

3.1 Observed hydrology and DOC

The mean annual precipitation (P) of the area was 787 mm yr^{-1} and the mean annual PET 935 mm yr^{-1} for the period ranging

25 from 01/04/2014 to 10/12/2017 (Tab. 2). WTD and DOC exhibited different dynamics between rewetted and control areas (Fig. 3b, c). The water table was close to the surface level in each piezometer during the wet season but the length of this season depended on the severity of the water table drawdown that occurred during the previous drier season. In 2014, a particularly wet year (P=906 mm and PET=904 mm from 01/04/2014 to 01/04/2015), the water table reached the surface in December 2014 while for the following season, which was relatively dry (P=736 mm and PET=960 mm from 01/04/2015 to

30 01/06/2016), it reached the surface in May 2016. The WTD was lower on average and with a greater variability in the control than in the rewetted area but the main difference between the sites was the severity of the maximum water table

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drawdown which was 26 cm in the rewetted and more than 43 cm in the control site, with the same climatic conditions for both locations.

The average of [DOC] measurements was 13.3±4.6 mg L^{-1} in the control site and 21.6±7.2 mg L^{-1} in the rewetted one. [DOC] were globally higher in the rewetted than in the control site ($p<0.001$) but this was especially true in the dry period. Overall, [DOC] were higher in dry periods than in wet periods for the rewetted site while this difference was not observed in the control site (Fig. 4a). Finally, when considering the temporal evolution of [DOC], the main difference was observed between April and October 2015 where [DOC] rose in the rewetted but decreased in the control site (Fig. 5).

The PARAFAC analysis revealed three main components characterizing the DOM (Fig. 4b). According to the review by Fellman et al. (2010), the first component (ex 360, em 466) can be described as high-molecular-weight and humic and is referred to here under its original name as C. The second component (ex 330, em 407) can be described as low-molecular-weight and is referred to here as M. The third component (ex 250, em 446) can be described as high molecular weight and humic and is referred to here as A. Component A is known to be more aromatic than C (Fellman et al., 2010), even if in our case, the shorter emission wavelength for component A than for C may also indicate that C is more aromatic than A (McKnight et al., 2001). The ratio of the contribution of component C over the contribution of A and of the contribution of component M over the contribution of A in pore water samples of the wet and dry campaigns are presented in Fig. 4 (c and d). A large increase in the contribution of C relative to the contribution of A was observed in dry conditions in the rewetted area ($p<0.001$) while the ratio was similar for control and rewetted sites in wet conditions. Similarly, a significant increase in the contribution of M relative to the contribution of A was observed during dry conditions in the rewetted site compared to wet conditions in control and rewetted areas ($p<0.001$).

3.2 Hydrological modeling

The best simulated and the observed WTD dynamics are shown in Fig. 3. NS and Br2 were greater than 0.10 and 0.24 for calibration periods and reached values greater than 0.10 and 0.39 for validation periods, respectively. The RMSE ranged between 1 and 9 cm and no drop in the model performance was observed for the validation period, compared to the calibration ones (Tab. 3). The model performed better for the wettest year in the control area and better for the intermediate and the driest years in the rewetted area. The important point is that the model was able to reproduce two different WTD dynamics using the same input data (i.e. rainfall and PET). These differences are explained by the modification in calibrated parameter values. As the evapotranspiration coefficient and maximum infiltration rates were the same for each site, the differences are driven by the discharge coefficients. The values of the three discharge coefficients (α_p, α_r and α_{sr}), corresponding to the intensity of the drainage of the three reservoirs (Se, Sm and Sr), were higher in the control site than in the rewetted one (Tab. 3). These differences were reflected in the water balance of each location with a lower water discharge (Q) in the rewetted site than in the control one (Tab. 2). However, fast superficial drainage (O) was higher in the rewetted site than in the control one, in contrast to the slow deep drainage (R+D). This is confirmed by the uncertainty analysis, which showed that despite large uncertainties in flows (80 to 250 mm) the difference between overland flow and

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drainage flow in the two sites is significant. Finally, sensitivity analysis indicated that the model is the most sensitive to the evapotranspiration coefficient in the growing season and the Se discharge coefficient, and the least sensitive to the evapotranspiration coefficient in the dormant period and the Sr discharge coefficient for both locations (Tab. 4).

3.3 DOC dynamics modeling

5   Simulated and observed pore water [DOC] are shown in Fig. 5. The simulations presented a RMSE < 9 mg L^{-1} for calibration and RMSE < 11 mg L^{-1} for validation in both rewetted and control sites, and with no systematic overestimations or underestimations. The model performed better for the control than for the rewetted site, except for the driest year (Tab. 5). The model was able to reproduce [DOC] dynamics in both locations, especially the rising concentrations in the rewetted site and the decreasing concentrations in the control site during summer 2015 (Fig. 5). The DOC balance was computed for each

10   location and is shown in Tab. 2. Overall, DOC exports were similar higher and in the same order of magnitude for each location. Nevertheless, a difference can be observed for the partitioning between exports from the Se and Sm reservoirs. While 44% of the total DOC exports originated from Se in the control site, exports from Se only account for 0.02% of the total DOC exported in the rewetted site (Tab. 2). Fig. 6 shows the temporal dynamics of simulated daily DOC exports for each location. DOC exports were episodic in both locations with the highest peaks for the control site during the wettest year

15   and the highest peaks in rewetted for the driest year. The minimum daily export rates were higher in the control than in the rewetted site.

4 Discussion

4.1 Hydrological processes

In this study, observed water table dynamics were used to better understand the dominant hydrological processes taking

20   place in two locations of a restored peatland (rewetted and control), by calibrating a conceptual model. Though simple (6 calibrated parameters), the model was able to reproduce the specific water table dynamics in each location of the studied area, using the same input data (precipitation and potential evapotranspiration). This difference in observed water table dynamics (17 cm of difference for the maximum water table drawdown) is reflected in the calibrated parameter values for each location (Tab. 3). In addition, and in order to better assess the dominant processes, a sensitivity analysis of the model

25   was performed for each location (Tab. 4). The results indicate that the most sensitive parameters are Kcg and αp which are related to the evapotranspiration during the growing season and the deep drainage of the retention reservoir (Se), respectively, meaning that these processes are the most important ones to explain the peatland hydrology. While evapotranspiration coefficients are the same for both sites, the drainage coefficient of the retention reservoir is the highest for the control location and this difference may explain the dissimilarity in the severity of the observed water table drawdown

30   and simulated water table balance in the two locations. Overland flow (O) accounts for 56% of the total discharge in the rewetted site while it represents less than 1% of the total discharge in the control one. At the contrary, deep drainage (D)

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represents less than 1% of the total discharge in the rewetted site and 24% in the control one it. This difference in the partitioning between fast superficial and slow deep discharge can be related to the restoration work, since the blockage of the drain could have reduced the deep drainage and increased the amount of surface drainage in the rewetted area. While the difference in water table dynamics between the two locations can be explained by other factors than restoration (e.g. geomorphological settings and vegetation cover), observations showed that the restoration work created an inundated area in its vicinity, in agreement with the results of Wilson et al. (2010) indicating that the frequency of full saturation of the peat increases markedly after a drain blocking operation. In addition, microtopography and vegetation cover are very homogenous over the area and these factors cannot explain the observed differences in water table dynamics between the two locations. Therefore, in this case, the model can help to characterize the impact of restoration as seen in the water balance and the value of the deep drainage coefficients. It enables deep drainage dominated (control) and surface drainage dominated (rewetted) systems to be identified within the same peatland, in relation with hydrological restoration work.

4.2 DOC dynamics control factors

4.2.1 Simulation results

A module simulating DOC production and loss was added to the hydrological model in order to better understand DOC dynamics in the two peatland locations, with RMSE between 1.6 and 10.8 mg L^{-1} for the different calibration and validation periods. However, the quality of the results is more difficult to assess than for the hydrological model because few data were available for the calibration and validation steps. Nevertheless, it is noteworthy that the model, based on only 2 calibrated parameters, is able to capture the two different dynamics recorded in each location, i.e. rising [DOC] in the downstream location in summer 2015 and a decreasing [DOC] in the upstream location in the same period.

4.2.2 DOC concentrations and control factors

Long-term studies have reported decreasing pore water [DOC] more than 10 years after a restoration operation took place (Höll et al., 2009; Wallage et al., 2006), while others observed increasing [DOC] after restoration (Hribljan et al., 2014; Strack et al., 2015). Glatzel et al. (2003) observed an increase in pore water [DOC] following a drain blocking operation but predicted a decrease in [DOC] with time due to a depletion of easily decomposable organic matter in the peat. In this study, the results indicate that, during the three years following a restoration operation, [DOC] were higher in the rewetted than in the control location during the dry period (from 1st of June to 30th of November), while they were similar during the wet period. In addition, the difference in [DOC] dynamics is also reflected in DOM quality inferred from its fluorescence properties, with a greater increase in low molecular weight compounds (component M) and fewer aromatic high molecular weight compounds (component C) in the rewetted location during the dry season compared to the control area. These findings are in agreement with the studies by Höll et al. (2009), Hribljan et al. (2014) and Strack et al. (2015) who observed

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that wetter sites would result in a pore water with smaller and fewer aromatic dissolved organic molecules (likely sourced from inputs of fresh litter from growing vegetation) than the sites with a lower water table.

The main difference in [DOC] is observed during the dry period, when the water table dynamics is different between the two locations. This would confirm that hydrology, and especially the magnitude of the water table drawdown, might be a major factor controlling [DOC] dynamics in the peatland. Indeed, the higher WTD in the dry period in the rewetted site is related with a higher [DOC] than in the control site where the WTD is lower. A larger proportion of low aromatic DOC is also observed during the same period in the rewetted than in the control site. Therefore, we propose to explain the differences in [DOC] by the difference in water table drawdown in the dry period. When the water table drawdown is small (high water table), more DOC is produced from the top peat layer containing more recent and easily biodegradable organic matter than when the water table drawdown is more severe (low water table). In addition, anaerobic conditions in the rewetted site would lead to less efficient decomposition of organic matter, increasing the production of water-soluble intermediate metabolites (Kalbitz et al., 2000; Strack et al., 2008). An increase in [DOC] in the rewetted location can also be explained by an increase in the photic zone, potentially supporting algae photosynthate production enhancing DOC release into the water column, as suggested by Hribljan et al. (2014). However the latter hypothesis is the least probable in our case since no ponding water is observed in summer in the study area. The ability of the model to reproduce pore water [DOC] dynamics can be attributed to its consideration of the water table drawdown which is expressed in the model through the use of soil moisture (based on water level in the Sm and Se reservoirs) as a production rate modifier. Finally, while this study focuses on the hydrological control on DOC dynamics, it is important to note that other factors not directly integrated in the model are also known to affect DOC exports such as pH and redox state (e.g. Grybos et al., 2009; Knorr, 2013).

4.2.3 DOC exports

The model enables DOC exports to be estimated for each location (Tab. 2). The results (values) are in the range reported in the literature (from 4.2 to 18.9 g-C m^2 yr^{-1}, Birkel et al., 2014, 2017 and Jager et al., 2009). DOC exported from the control site is slightly higher than that from the rewetted one but in the same order of magnitude, even when considering uncertainty in fluxes. The reduction in DOC exports, for the best fit simulation, has to be related to the increase of the amount in quick surface overflow in the rewetted site which is characterized by a low [DOC], and therefore low DOC exports. In the rewetted site, the water does not infiltrate in the already saturated peat porosity and while [DOC] increases, DOC exports decreases. In addition, the partitioning between DOC exports from the two production reservoirs is clearly different for each location. According to the water balance, DOC exports are mainly driven by the drainage from the Sm reservoir in the rewetted site while the amount of DOC exported through deep drainage and runoff is more balanced in the control site. This clearly reflects the dominant hydrological processes in each location and can be seen in the temporal variability in DOC exports (Fig. 6). DOC exports are more episodic in the rewetted site, with 75% of the DOC exported during only 13% of the total simulated period length (47% of the total DOC export for the same period in the control site). These results are consistent with the results of Birkel et al. (2017) who highlighted the non-linearity of DOC exports in a peatland catchment and

reported that 60% of the DOC was exported in 30% of the time through rapid near-surface runoff in a small peat catchment. However, in the control site, DOC exports are less episodic than in the rewetted one in accordance with the dominance of a slow but regular deep drainage of the Se reservoir in this site. These results confirm that hydrology has a major impact on DOC load dynamics (e.g. Birkel et al., 2017; Tunaley et al., 2016), since it is the partitioning between superficial quick flow

5   and slow deep drainage that controls the temporal dynamics of DOC exports (Birkel et al., 2014). This study also suggests that this hydrological control on DOC fluxes also affects the source of DOC exported from the peatland, in relation with the difference in DOM composition observed with the fluorescence analysis. Therefore, in the rewetted area the DOC exported will exhibit characteristics of top peat layer recent organic matter (less aromatic) while it is likely derived from older and deeper organic matter (more aromatic) in the control area. These findings indicate that, while its impact on DOC loads can

10 be negligible, restoration work might have an impact on stream ecosystems by releasing a less aromatic DOM, especially during the dry season. However, these findings are valid for a three-year period following the restoration and might be different for the future, underlining the need for long term monitoring to correctly assess the impact of hydrological restoration on DOC dynamics.

15 **4.3 Perspectives for application of the model**

The model developed in this study follows a parsimonious coupled hydrology-biogeochemistry model philosophy (Birkel et al., 2014, 2017; Lessels et al., 2015). By keeping parametrization to a minimum, it was able to identify factors controlling WTD and DOC dynamics in the two contrasted sites of the studied peatland with a relatively low requirement in input data (precipitation, potential evapotranspiration and temperature). Contrary to similar models, hydrology is here calibrated on

20 WTD instead of on stream discharge. This way, the model proves to be a relevant tool to be applied in flat areas where catchment delineation is highly uncertain and outlets difficult to monitor. It is also useful to explore the hydrology of areas located within the same peatland by performing a multi-site calibration. However, it is necessary to perform an uncertainty analysis to better assess confidence in the computed fluxes when no data are available. The careful application of the model highlights the impact of hydrological restoration on hydrology and DOC dynamics that would have been difficult to study

25 with models calibrated on stream discharge and applicable at the catchment scale only. In addition, the DOC model developed in this study has shown good results in modeling pore water [DOC] dynamics, meaning that the 2 calibrated parameters model is adapted to simulate DOC dynamics in peatland ecosystems. Therefore, if applied to several WTD time series, it could provide spatial information by identifying the main areas of DOC production within a peatland. This model could also be applied to longer time series and different study sites to assess the effect of hydrological restoration over longer

30 periods, and the dominant controlling factors in peatlands with different settings.

5 Conclusions

A conceptual hydrological model, especially developed for peatland and calibrated on WTD, has been combined with a simple DOC production/loss model and applied to two locations of a peatland, one of them affected by hydrological restoration. The application of this model has shown the following:

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- The hydrological restoration was found to impact water balance, by increasing fast superficial drainage compared to slow deep drainage.
- The intensity of the maximum water table drawdown was found to be the main factor controlling pore water [DOC] dynamics in the peatland.
- Higher [DOC] in the rewetted location was linked to differences in DOM composition

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- Simulated DOC exports were in the same order of magnitude for rewetted and control locations, in a short-term period (3 years).
- Water partitioning between fast superficial drainage and slow deep drainage controls DOC sources as well as the temporal dynamics of DOC exports

These results suggest that hydrological restoration does not affect short term DOC fluxes in peatland. In addition, this study
15 has shown that the proposed conceptual hydrological and biogeochemical model can provide relevant information about water balance and the factors controlling element cycling processes in peatlands. The application of a WTD based model is a relevant alternative to a discharge calibrated catchment model when the outlet is not easily identifiable or when seeking for within-peatland spatial information.

20 *Author contributions*

FLa, SG and SB designed the study site restoration and monitoring.

LBJ, SG, FLa, FLe and LP helped with instrumentation and data collection.

CD, NJ and RZ helped with fluorescence analysis and data interpretation

LBJ and SB developed the model

25 LBJ performed simulations and data analysis

LBJ prepared the draft of the manuscript

FLe, SG, CD, NJ, FLa and SB helped improve the final manuscript

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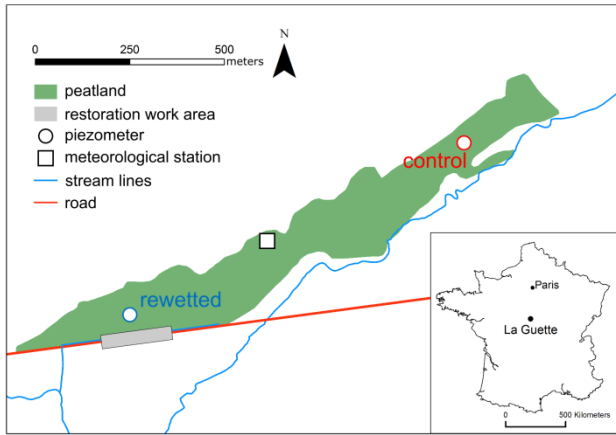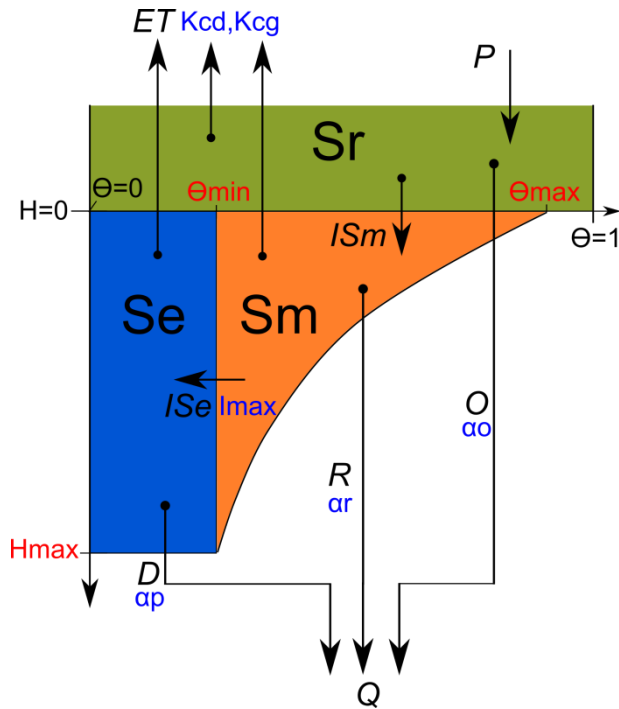
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Figures

Figure 1: Location and settings of the study area. Locations of control and rewetted monitoring are indicated.

5   **Figure 2: Structure of the hydrological model, composed of three reservoirs, surface (Sr), macroporosity (Sm) and retention (Se). The different fluxes are indicated in italics, P (precipitation), ET (evapotranspiration), ISm (infiltration from Sr to Sm), ISe (infiltration from Sm to Se), D (deep drainage from Se), R (runoff from Sm), O (overland flow from Sr). Total discharge Q corresponds to the sum of D, R and O. Note that given parameters are in red and calibrated parameters associated to each flux are in blue, see description in Tab. 1.**
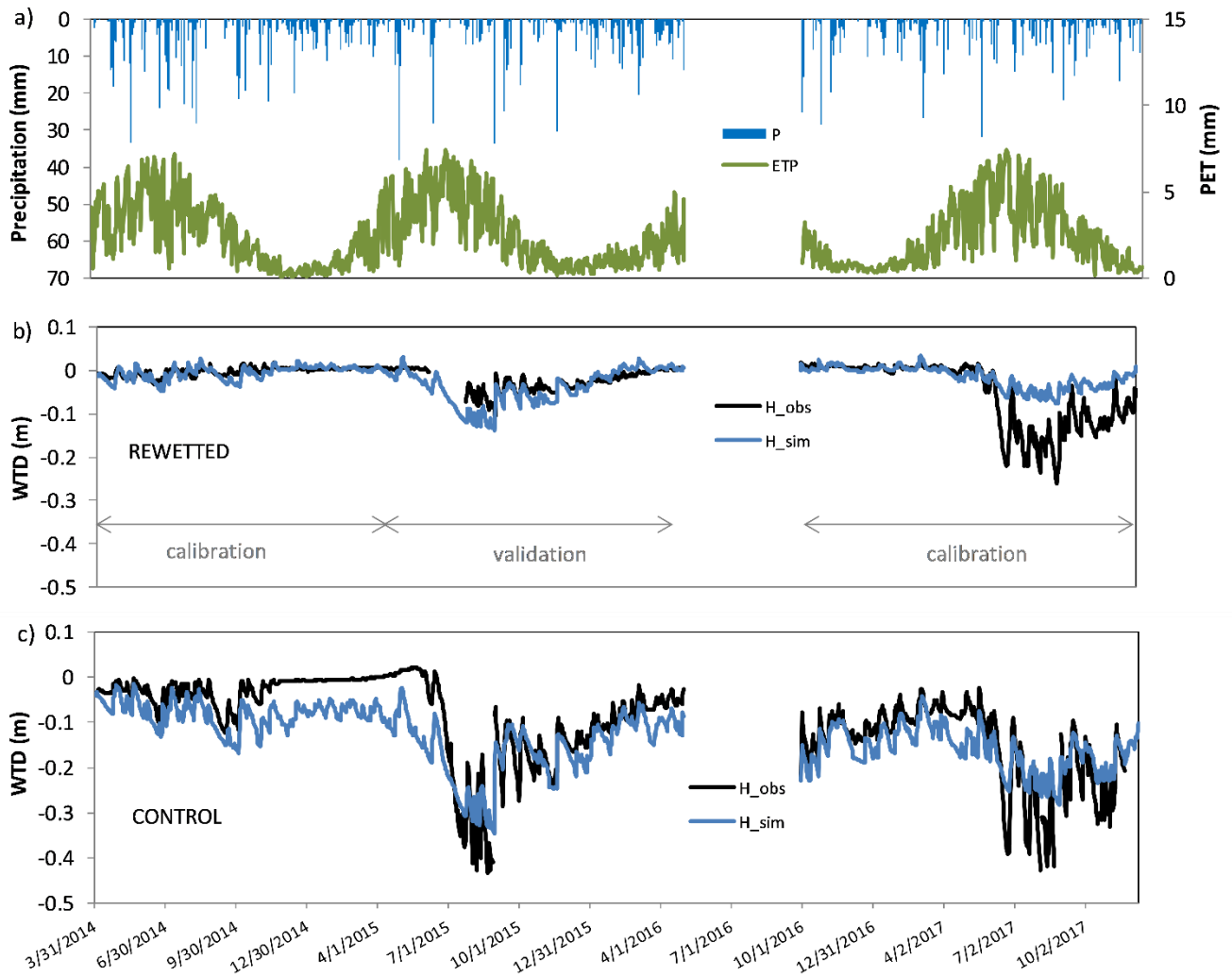
Figure 3: (a) Time series of meteorological data (PET, potential evapotranspiration and P, precipitation) used as input data in the hydrological model, **(b)** simulated and observed WTD in the rewetted site and **(c)** simulated and observed WTD in the control site. Calibration and validation periods are also indicated.
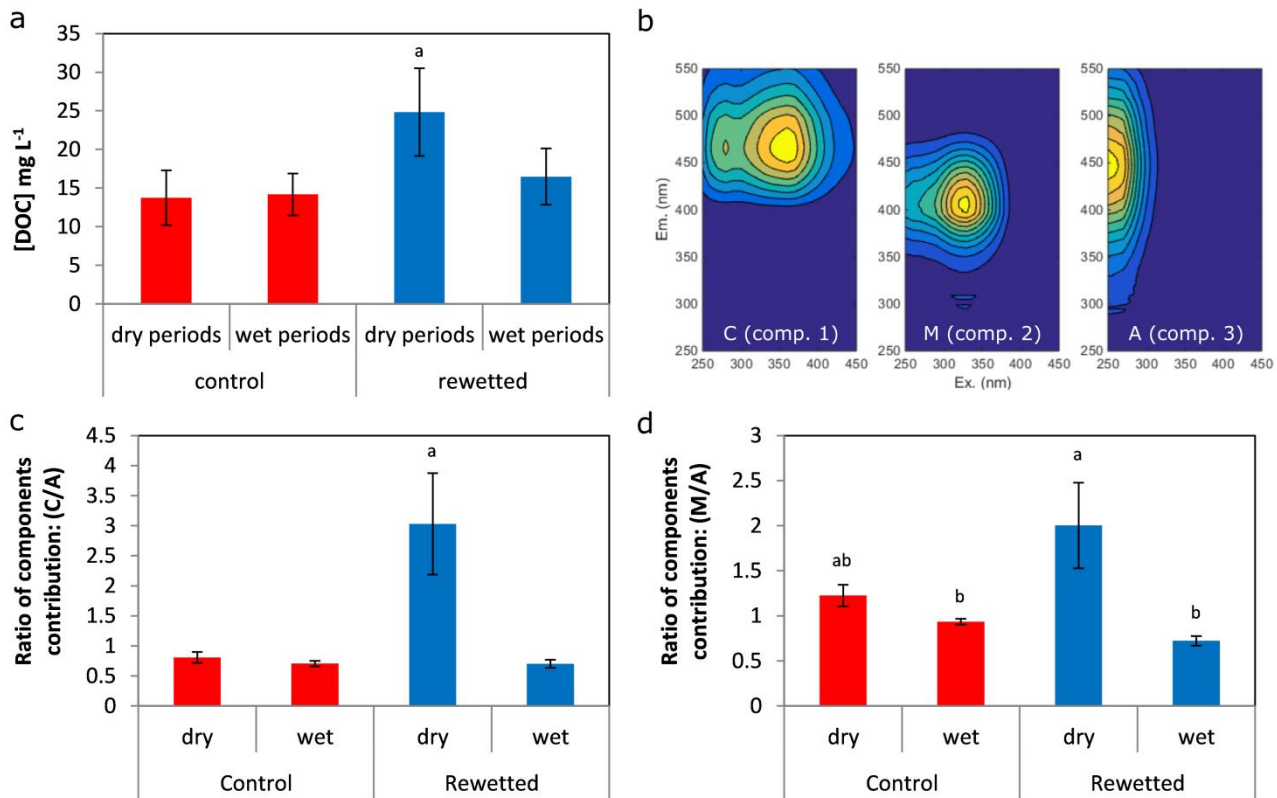
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Figure 4: (a) DOC concentrations in control and rewetted sites for dry (1st of June to 30th of November, n=7) and wet periods (1st of December to 31st of May, n=6).). **(b)** Excitation-emission matrices for the identified PARAFAC components (see the text for details). **(c)** Ratio of contribution of component C over component A for dry and wet conditions in control and rewetted sites (n=4). **(d)** Ratio of contribution of component M over component A for dry and wet conditions in control and rewetted sites (n=4). The letter above the bar indicates significant differences across different conditions (Tukey's p<0.01). **(b)** Excitation-emission matrices for the identified PARAFAC components (see the text for details).
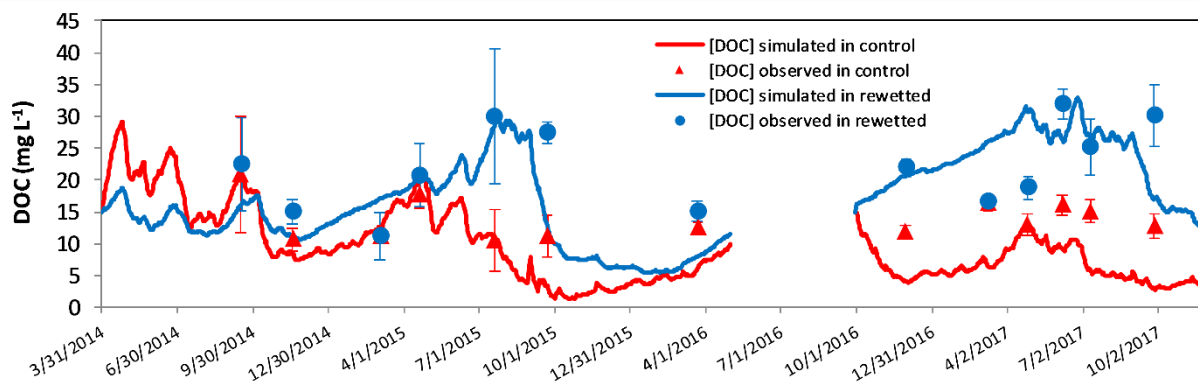

Figure 5: Simulated and observed pore water [DOC] in control and rewetted sites. Observations are the average of 4 samples for each sampling date. Error bars indicate standard deviation.
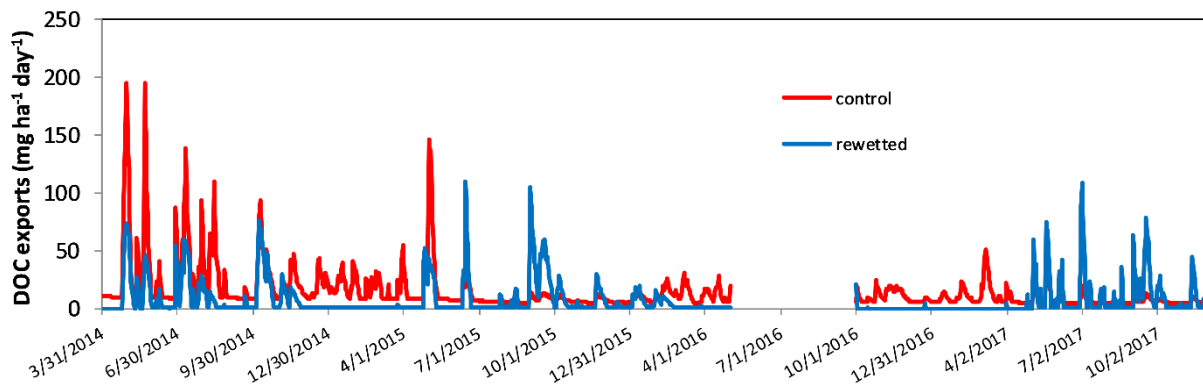
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Figure 6: Simulated DOC exports for control and rewetted sites.

Tables

Table 1: List of the parameters used in the hydrological and in the DOC model. The hydrological flux associated to each parameter is in parenthesis. Calibrated parameters and boundary condition independent (BCI) parameters are indicated.

	Symbol	Process	Description	Units	Calibrated
Hydrological	Hmax	WTD-moisture relation	Peat depth	mm	no
model	Θmin	WTD-moisture relation	Porosity at maximum depth	$m^3.m^{-3}$	no
	Θmax	WTD-moisture relation	Porosity at the surface	$m^3.m^{-3}$	no
	Kcd	Evapotranspiration (ET)	Crop coefficient for dormant season	-	yes (BCI)
	Kcg	Evapotranspiration (ET)	Crop coefficient for growing season	-	yes (BCI)
	Imax	Infiltration Sm to Se (ISe)	Maximum infiltration rates in Se	mm day^{-1}	yes (BCI)
	αp	Percolation rate from Se (D)	Discharge coefficient of Se	day^{-1}	yes
	αr	Runoff rate from Sm (R)	Discharge coefficient of Sr	day^{-1}	yes
	αo	Overland flow from Sr (O)	Discharge coefficient of So	day^{-1}	yes
DOC model	SOC	DOC module	Mass of TOC in peat profile	mgC mm^{-1}	no
	DOCrain	DOC module	DOC concentration in rain water	mg L^{-1}	no
	kprod	DOC module	DOC production coefficient	day^{-1}	yes
	kloss	DOC module	DOC loss coefficient	day^{-1}	yes

Table 2: Water and DOC balance computed for the simulated period (01/04/2016 to 01/04/2016 and 01/10/2016 to 10/12/2017) in rewetted and control areas. P is precipitation, ET is evapotranspiration, Q is total discharge, O is overland flow, R is macroporosity runoff, D is deep drainage. Best fit is indicated and 5th and 95th percentiles of the behavioural runs are between bracket.

	Rewetted (5th – 95th)	Control (5h – 5h)
P (mm yr^{-1})	787	787
ET (mm yr^{-1})	357 (284 – 374)	357 (284 – 374)
Q (mm yr^{-1})	417 (399 – 489)	466 (370 – 494)
O (mm yr^{-1})	233(188 – 394)	3.6 (0 – 40)
R (mm yr^{-1})	183 (42 – 220)	352 (20 – 355)
D (mm yr^{-1})	2 (1 – 79)	111 (102 – 444)
DOC exports total (g C m^{-2} yr^{-1})	3.6 (3.5 – 7.2)	8.6(8.5.7– 25.5)
DOC exports Se (g C m^{-2} yr^{-1})	0.1 (0.1 – 3.6)	3.8 (3.8 – 14.3)
DOC exports Sm (g C m^{-2} yr^{-1})	3.5(3.1 – 3.6)	4.8(0.9– 11.5)

Table 3: Calibrated parameters and efficiency criteria for the different periods of calibration and validation. Ranges of parameters used for autocalibration are also indicated.

	Rewetted	Control	Range
Kcd	0.37	0.37	0.01 – 0.5
Kcg	0.40	0.40	0.4 – 0.8
Imax	0.84	0.84	0.2 – 5
αp	1.6E-05	1.9E-03	0 – 0.01
αr	0.20	0.37	0 – 0.5
αsr	0.20	0.27	0 – 0.5
Calibration (2014/15)			
NS	0.10	0.61	
Br2	0.52	0.67	
RMSE (m)	0.01	0.01	
Calibration (2016/17)			
NS	0.25	0.16	
Br2	0.26	0.24	
RMSE (m)	0.065	0.080	
Validation (2015/16)			
NS	0.10	0.30	
Br2	0.54	0.39	
RMSE (m)	0.02	0.09	

Table 4: Sensitivity rank of the parameters of the hydrological model

Parameter	*Sensitivity rank*	
	Rewetted	Control
Kcg	1	1
αp	2	2
αr	4	3
Imax	3	4
αo	6	5
Kcd	5	6

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Table 5: Calibrated parameters and efficiency of the DOC model

	Rewetted	Control
kprod	5.0E-08	9.0E-07
kloss	5.0E-04	1.2E-02
Calibration (2014/15)		
RMSE (mg.L^{-1})	5.4	1.6
Br2	0.003	0.89
Calibration (2016/17)		
RMSE (mg.L^{-1})	8.6	8
Br2	0.18	0.03
Validation (2015/16)		
RMSE (mg.L^{-1})	8.9	10.8
Br2	0.34	0.31