Journal of Hydrology 499 (2013) 132–139

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A water-table dependent reservoir model to investigate the effect of drought and vascular plant invasion on peatland hydrology

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ARTICLE INFO

Article history:
Received 20 December 2012
Received in revised form 12 June 2013
Accepted 19 June 2013
Available online 26 June 2013
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Magdeline Laba, Associate Editor

Keywords:
Peatland
Hydrological model
Water balance
Storage capacity
Plant consumption

SUMMARY

This paper investigates the peat saturation and the air entrapment dynamics in a peatland, estimated from the water table fluctuations. A reservoirs model of water table fluctuations in a double-porosity peat is proposed, by calculating the stored water in effective porosity of the peat from precipitation and evapotranspiration datasets. Calculations conceptualize vascular plant consumption through a crop coefficient. Changes in water storage, located in the effective porosity of the peat, are described through a maximum infiltration rate and a maximum storage capacity. Water discharges take place in runoff and percolation reservoirs. The runoff coefficient is considered to be water table dependent. This model was tested on a peatland that has experienced strong water table fluctuations caused by summer drought and/or by vascular plant water consumption. A water table dependent runoff model appeared to be adequate to describe the water table fluctuations in peatland. From this model, vascular plants were found to increase the crop coefficient and to limit percolation through the peat. The high water table depth in winter was found to change with the years and is related to an equilibrium between slow infiltration in peat versus percolation plus evapotranspiration. In this disturbed peatland, even if overland flows occurred after a drought, the re-saturation of effective porosity was slow with about 30% of air trapped in the porosity 6 months after the drought period. The effects of a drought on peat saturation were observed over more than a single hydrological cycle. This can affect the biogeochemical processes controlling the C cycle in peatland.

1. Introduction

Peatland ecosystems are the major natural continental carbon (C) store as well as an important CH_4 source (Gorham, 1991; Morris et al., 2011). Their response to global change is uncertain as positive or negative feedback can be triggered (Lashof et al., 1997). This uncertainty creates the need to better assess and predict their C source or sink functioning to be able ultimately to take the peatland contribution into account in the global climate model (Limpens et al., 2008). In the carbon cycle, hydrological functioning controls the physical, chemical and biological processes (Weiss et al., 2006) and hence is one of the most important factors regulating carbon fluxes.

The usual hydrological conceptual model in peatland, according to Ingram's definition (1983), distinguishes an acrotelm and a catotelm layer. The acrotelm is affected by a fluctuating water table (WT). It is the compartment that supports the growing vegetation and where most of the biological activities take place. The catotelm is a waterlogged compartment which is permanently anoxic and where microbial communities are composed only of strict anaerobic organisms (Holden and Burt, 2003). Linked to this microbial activity, Moore and Knowles (1989) showed in laboratory experimental studies of peat cores that the molar ratio of CO_2 and CH_4 emission may rise from as low as 10 with the WT 10 cm above the peat, to >10,000 when the WT is 70 cm below the peat surface. This relationship between WT and biogeochemistry is also observed in other multi-porosity aquifers, where successive WT fluctuations change the water bicarbonate content in response to CO_2 dissolution and modify the water exchanges between the different reservoirs of the aquifers (Charmoille et al., 2009). Thus, because of the control the WT exerts on gas availability within the peat column, WT depth and variations are key factors in understanding the C cycle.

Under environmental changes (such as global warming, precipitation changes or vascular plant invasion), the WT dynamics can change and create feedback effects on the C cycle. Frequent WT drawdowns creating a deeper and thicker acrotelm than is

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http://dx.doi.org/10.1016/j.jhydrol.2013.06.035

observed in intact peatlands may lead to (1) further degradation, (2) to a reinforcement of the erosion phenomena caused by runoff (3) to a change the water quality (Daniels et al., 2008) and (4) to a modification in evapotranspiration (Restrepo et al., 1998). This is also evidenced in harvested sites where drainage and peat extraction lower the WT, expose relatively decomposed peat and increase the runoff (Van Seters and Price, 2001), whereas creating artificial drain blocking increases the WT, modifies the runoff and the water quality (Worrall et al., 2007).

To explore WT impact on hydrological processes (runoff and infiltration) and on the carbon cycle, some studies have monitored peatlands located in areas with a higher average air temperature than in sub-boreal peatlands (Rosenberry and Winter, 1997; Sarkkola et al.2009; Gogo et al., 2011a). The mechanisms described in these kinds of peatlands can help to understand how ecosystems situated in high latitudes may react to global change. From a hydrological point of view, the peatlands located in these areas may experience strong summer drought, high WT fluctuations and even higher precipitation (IPCC, 2008).

The second step is to model these mechanisms to propose prospective scenarios. For large scale areas and for geochemical modeling, hydrologists usually prefer to apply a reservoir model with a limited number of calibrated parameters (Perrin et al., 2001; Violette et al., 2010). To do so in peatland, hydrological models are based on the regular concept of soil hydrology (Restrepo et al., 1998). Most hydrological peatland models focus on runoff production (e.g. Quinton and Marsh, 1999; Tetzlaff et al., 2007). Few of them try to model the WT dynamics to evidence the WT control on peat saturation and on gas availability within the peat column.

In this paper, to link WT and peat saturation, a reservoir model of WT fluctuations in peat is proposed based on a literature review. The aim was to identify the four parameters that explain more than 80% of the WT fluctuations, from the precipitation and evapotranspiration datasets. The calculations include: vascular plant consumption through a “crop” coefficient, water supply of peat through a maximum infiltration rate and a maximum water storage capacity and the flows with runoff and percolation coefficients. To improve the description between the WT and other parameters, the runoff coefficient is considered to be WT dependent. This model was tested on a peatland that has experienced strong WT fluctuations caused by summer drought and/or by vascular plants. Analysis of this model calibrated with a field dataset evidences that, in peatland showing a wide range of water table fluctuations, the re-saturation of effective porosity was slow with about 30% of air trapped in the porosity 6 months after the drought period. This slow re-saturation can affect the biogeochemical processes controlling the C cycle in peatland.

2. Materials and methods

2.1. Study site

The site studied is La Guette peatland (Fig. 1) located in Neuvy-sur-Barangeon in the South-East part the French Région Centre, 200 km south of Paris (altitude: 160 m, N: 47°19′, E: 2°16′). The site is composed of patches of acidic *Sphagnum* fen with peaty heathland dominated by *Calluna vulgaris* and *Erica tetralix*. The site is colonized by *Molina caerulea* and *Betula spp* (*Betula pendula* and *Betula pubescens*). The dominant *Sphagnum* species are *Sphagnum cuspidatum* and *Sphagnum rubellum*. The maximum peat thickness is 2 m.

2.2. Field and laboratory measurements

In March 2009, 268 measurements of WT elevations were made with a level (for elevation) and a Global Positioning System (for *x* and *y* location) to produce a WT map and to delineate the catchment area of the peatland. The horizontal accuracy was 2 m, the elevation accuracy was 1.8 cm. The results are presented in Fig. 1, using a flow accumulation method (Gruber and Peckham, 2009) in a Geographic Information System.

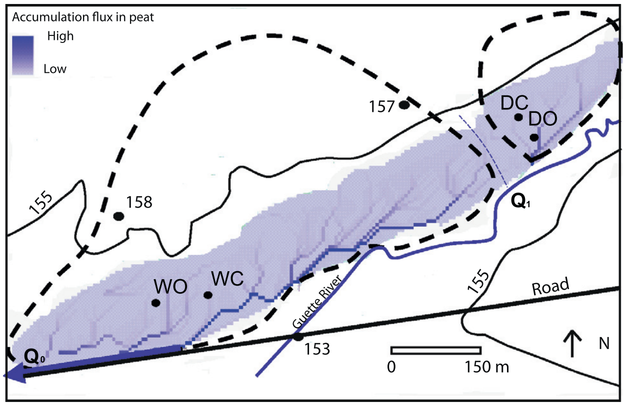

Fig. 1. Map of the la Guette peatland: location of the peatland (blue), of the piezometers (WO, DO, WC and DC); accumulation flux of water calculated from the piezometric map (blue lines), watersheds (dashed lines) and discharge areas (Q0 and Q1). Elevation in meter above sea level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Precipitation (PP) was recorded by the French weather institute (Meteo-France) 0.8 km from the peatland and potential evapotranspiration (ET0) was calculated using a Penman formula from data recorded in the town of Bourges (25 km south-east of the peatland). For the thirty-year period 1971–2000 in Bourges, annual average precipitation was about 732 mm and annual average ET0 about 831 mm. Between 2008 and 2011, precipitation and ET0 were about 700–767 mm and 862–964 mm, respectively. Daily records were not available for the catchment for the overall period of the WT monitoring. The precipitation and ET0 datasets were validated by comparing the dataset from the weather institute with datasets from a Campbell scientific weather station® installed on the peatland catchment in 2010. For the years 2010–2011, the comparison shows a 1.0 slope and a regression coefficient of about $R^2 = 0.98$ for the precipitation dataset.

Runoff was measured manually at the Q0 discharge point using a dilution method (described in Binet et al., 2007). An automatic device was installed during the fall of 2011. As the discharge area can be connected with the river during the high water level period, the data do not represent only the outflow of the peat. Manual measurements were performed on each field trip if the river was not connected to the drainage zone.

Within the peatland the WT levels were monitored in four sites: in the western part, site WO is dominated by open vegetation and site WC is dominated by *Molinia caerulea* and especially *Betula spp* vegetation. From the 70th, this two species tend to invade the peatland. These species overgrow *Sphagnum* species which tend to “close” the system, which was initially dominated by these bryophytes. Two sites were located in the eastern part of the peatland: site DO has an open vegetation and site DC has a closed vegetation (by *Molinia caerulea* and *Betula* spp) (Gogo et al., 2011b).

Shallow wells were installed to provide data on the fluctuations of the WT for the four sites (Fig. 1). These wells were constructed by hand-augering a hole and installing a PVC screen and a pipe 5.1 cm in diameter. The depth was about 1.2 m. As peat depth was less than 1 m in the four monitoring sites, the four wells were instrumented with a WT monitoring system (OTT® Orpheus mini and Orphimede). WTs were queried each hour by a data logger and the logs were averaged to provide daily heads. Manual check measurements were made on each field trip to validate the automatic measurements. Water-level accuracy was about 0.001 m.