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Contribution of rainfall *vs.* water management to Mediterranean wetland hydrology: Development of an interactive simulation tool to foster adaptation to climate variability

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A R T I C L E I N F O

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A B S T R A C T

Mediterranean wetlands are increasingly managed to maintain their functions and services following modification in water allocation, embankment and climate change, calling for proactive and adaptive water management. In a first step, we used long-term monitoring of water levels in 37 adjacent embanked marshes in the Camargue as a repeated non-controlled experiment to build a hydrological model. Without information on water input/output by marsh users, we could nevertheless estimate evapotranspiration under flooding and dry conditions, and soil water coefficient. The model provided a high predictive accuracy (adjusted $R^2 = 0.73–0.83$) of monthly water levels when applied to an independent sample of 12 marshes. In a second step we developed an interactive decision-aid tool that allows users to visualize the impact of their management strategy (desired water level at a specific month) on subsequent water levels, and their consequence on different components of the ecosystem over a 10-yr period.

Software availability

Software name: Mar-O-Sel
Developer: Christophe Germain
Year first official release: 2014
Hardware requirements: Any device
System requirements: Internet access
Software requirements: Internet Browser (tested with Internet Explorer (V ≥ 9), Chrome & Firefox
Program language: php and MySQL (server side), HTML and JavaScript (user side)
Software language: French, English
Availability: www.Mar-O-Sel.net
License: Free – Open source (code available upon request)

1. Introduction

Hydrology is a prime factor influencing wetland functions, biodiversity and services (Coops and Hosper, 2002; Janssen et al., 2005). In semi-permanent and brackish environments, seasonal variations in water levels are particularly crucial for the maintenance of emerged and submerged macrophytes and their associated fauna (Bolduc and Afton, 2004; Osland et al., 2011). As a result of urban and agricultural development, palustrine wetlands (shallow lakes, marshes, ponds) are often disconnected from most of their catchment area, requiring active water management to maintain or enhance their functions (Tamisier and Grillas, 1994; Janssen et al., 2005). Further reduction in freshwater availability either due to modification in land use, water allocation, or climate variability is increasingly threatening biodiversity and human uses of wetlands (Lyons et al., 2008; Germer et al., 2011). Preserving wetlands functions and services is a priority of the European Water Framework Directive, with management of water scarcity being recognized as a major future challenge in southern Europe (European Commission, 2010). Proactive and adaptive water management should hence be encouraged in the Mediterranean region, which is already characterized by a hydric deficit during the summer period (Zacharias et al., 2005; Beklioglu et al., 2007). Although many studies emphasize the importance of hydrology for wetlands, it remains one of the least understood components of these ecosystems (LaBaugh, 2007). Studies in hydrology are typically carried out at the watershed scale, using site-specific physical variables and

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costly instrumentation (Stannard et al., 2013). Downscaling this approach to a marsh would result in a low potential for generalisation and a level of precision well beyond that required by the wetland manager. On the other hand, measurement of water levels is frequently included by wetland managers in their monitoring scheme. These long-term data can be considered as repeated non-controlled experiments of which the combination can serve to describe and understand a hydrological system. For a seasonal marsh having fine sediments as substrate and connected to a confined water table, four types of information are required to build a hydrological model: rainfall, temporal variation in evapotranspiration under flooding and dry conditions, and the amount of water needed to saturate dry soil.

This study presents an original empirical approach to hydrological modelling based on the monitoring of water levels initiated within a LIFE Nature project on reedbed management and restoration for Eurasian bitterns in 2001. We created a hydrological model using a 10-yr dataset on bimonthly water levels from 37 adjacent marshes and precipitation data from a nearby meteorological station. Monthly evapotranspiration rates and soil water coefficient were deduced by selecting appropriate parts of the dataset using simple statistical rules. From this model, an interactive simulation tool was developed to orient management decisions within a context of short and long term variability in climate conditions, which temporally affects availability of freshwater pumped from the Rhône River caused by increased salinity in low-flow periods.

In this paper, we explain the reasoning of the model building and the options provided by the generic interactive tool Mar-O-Sel. A validation of the model is presented using an independent dataset of 12 marshes of different sizes and vegetation types. A first application of Mar-O-Sel is used to estimate temporal hydrological patterns of the study marshes under the hypothetical scenario of no water supply, using a 21-year meteorological dataset. These results are briefly discussed in terms of ecological consequences on the maintenance of these socio-ecosystems in the Mediterranean region. A second application of the model is provided through a case study aiming at maximising the carrying capacity of a marsh to waterbirds while minimising water inputs and respecting the natural cycle of Mediterranean wetlands.

2. Methods

2.1. Study site

Located in the Camargue, southern France, the study site corresponds to 2000 ha of marshes divided into 37 hydrological units embanked and disconnected from their catchment area, except under exceptional flooding episodes (Fig. 1). These marshes are actively managed for different uses among reed harvesting, waterfowl hunting, fishing, cattle grazing and nature conservation (Poulin et al., 2005). Because seasonal water needs differ among human activities, conflicts arise among land owners ($n = 29$) and users (>200) with spurious interventions on hydraulic structures. Accordingly, information on when and how much water is entered to or evacuated from the system is not available.

The substrate of these marshes, which are totally or partially covered with common reed *Phragmites australis*, is dominated by very fine sediment (silt and clay) covered by a 10–60 cm layer of organic matter. Mean reed density varies from 120 to 556 stems/m^2 based on 292 quadrats of 50 × 50 cm spread throughout the marshes (Poulin et al., 2005). Some other emergents (ie. *Bolboschoenus maritimus, Typha angustifolia*) are locally present at low density, while hydrophytes (ie. *Potamogeton pectinatum, Myriophyllum spicatum, P. pusillus* and *P. crispus, Najas marina,* and *Chara* spp) can be found in open-water areas. The climate is Mediterranean with a mean annual rainfall of 694 mm occurring mostly in April and October–November. Mean lowest and highest daily temperatures are 2.7 °C in January and 31 °C in August. Meteorological data were obtained from the Saint-Gilles Météo France station located 10 km from the study site (Fig. 1).

2.2. Field data

Water level data were collected from 37 PVC tubes 8-cm wide, 180-cm tall and buried 50-cm into the ground, each one located in a different hydrological unit of the Charnier–Scamandre marshes. The dataset consists of surface and underground water levels collected twice monthly since April 2001 during at least a year over a 10-yr period. Water levels were measured outside (flooding condition) or inside (drought condition) the PVC tube using the external and internal air draughts calculated from the water surface to the top of the tube.

2.3. Building of the hydrological model

The difference between two consecutive water level measures were calculated and assigned to either one of two groups: positive values (water input) and negative values (water evapotranspiration). A simple statistical rule was defined according to an iterative procedure to detect water input smaller than water evapotranspiration: any value lying above the maximal 99% confidence interval of monthly evapotranspiration was assigned to water input. Calculation of mean evapotranspiration was made easy because rainfall is relatively rare and clumped over short periods in the Mediterranean region. The two groups were further divided in two sub-groups whether water increase or decrease occurred when the ground was flooded or dry in order to permit the calculation of evapotranspiration under flooding and dry conditions, as well and the amount of water needed to saturate soil. Rainfall data were compiled according to the same timeframe as the water level data, twice monthly for model building, monthly for model validation and application.

2.4. Model performance

Our estimation of monthly evapotranspiration values were compared to a power-relation transformation of the Penman equation (Penman, 1948) based on real evapotranspiration calculated from reed mesocosm controlled-experiments carried out in the Camargue (Chauvelon, 1996). To validate our hydrological model, a cross-validation procedure was applied to 12 independent marshes located on nature reserves in the Camargue (Tour du Valat and Marais du Vigueirat, Fig. 1 and Table 1) where time series of water level measurements were available, and for which periods of water input or output were known. Because the model calculates a water level at the end of each month and measurements can be taken at anytime during a month, water levels were extrapolated using a linear relationship between two measures to get a value for the end of each month. Parameters related to catchment area, dyke height, dyke water tightness, and soil porosity were estimated iteratively by model fit. Water inputs or outputs were incorporated to the model at each of the periods identified by the manager, with the unknown amount of water defined iteratively through model fit. In some cases, managers knew that there were uncontrolled water input and these episodes could be easily identified by the model and integrated to the management actions.

Model performance was estimated by direct value comparisons using simple metrics (mean and variance), by computing the statistical properties of real values plotted against predicted values