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Short Communication

Coupling hydrological modeling and support vector regression to model hydropeaking in alpine catchments

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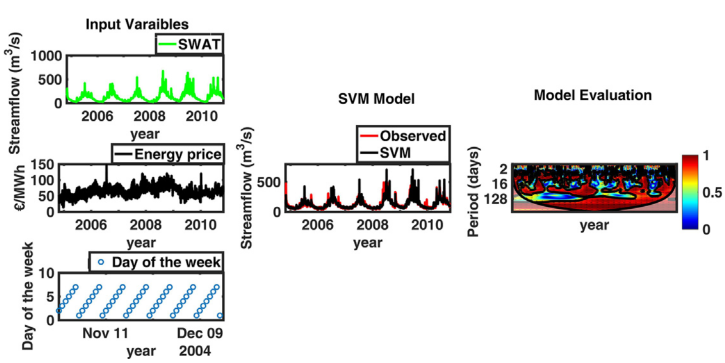
HIGHLIGHTS

- Streamflow displays high coherence with energy price, particularly during winter.
- Coupling of hydrological model and support vector machine (SVM).
- Coupled model can reproduce anthropogenic influences on streamflow.
- Coupled model displays the highest coherence with the observation at 3–7 day scales.

GRAPHICAL ABSTRACT



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ABSTRACT

Water management in the alpine region has an important impact on streamflow. In particular, hydropower production is known to cause hydropeaking i.e., sudden fluctuations in river stage caused by the release or storage of water in artificial reservoirs. Modeling hydropeaking with hydrological models, such as the Soil Water Assessment Tool (SWAT), requires knowledge of reservoir management rules. These data are often not available since they are sensitive information belonging to hydropower production companies. In this short communication, we propose to couple the results of a calibrated hydrological model with a machine learning method to reproduce hydropeaking without requiring the knowledge of the actual reservoir management operation. We trained a support vector machine (SVM) with SWAT model outputs, the day of the week and the energy price. We tested the model for the Upper Adige river basin in North-East Italy. A wavelet analysis showed that energy price has a significant influence on river discharge, and a wavelet coherence analysis demonstrated the improved performance of the SVM model in comparison to the SWAT model alone. The SVM model was also able to capture the fluctuations in streamflow caused by hydropeaking when both energy price and river discharge displayed a complex temporal dynamic.

1. Introduction

Alpine catchments play a pivotal role in Europe for water provisioning as well as for hydropower production (Hastik et al., 2015; Viviroli and Weingartner, 2004; Wagner et al., 2015). Fluctuations of river

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discharge occur at multiple temporal scales due to natural and anthropogenic driving forces (Poff et al., 2007; Rahman et al., 2013). Therefore, water management in these catchments strongly influences the hydrological cycle and vice versa (Basso and Botter, 2012; Beniston, 2012). Dams and hydropower plants greatly impact alpine rivers, because they generate highly variable river stage fluctuations. Hydropeaking i.e., the artificial increase and decrease of discharge and corresponding water levels in rivers (Hauer et al., 2017b) is particularly relevant because it threatens ecosystem integrity (Botter et al., 2010; FitzHugh and Vogel, 2011; Garcia et al., 2011; Hauer et al., 2017a; Holzapfel et al., 2017; Zolezzi et al., 2009).

Modeling hydrological processes in alpine catchments requires that the coupled interaction between natural processes and economic drivers, which control hydropower production, are taken into account (Gaudard et al., 2014; Tonolla et al., 2017). Several models exist in the literature to reproduce reservoir operation and have been successfully applied in several case studies (e.g., Finger et al., 2012; Majone et al., 2016; Rahman et al., 2013; Rahman et al., 2014). However, data availability is one of the main challenges in reproducing streamflow when considering reservoir operation for hydropower production (Gaudard et al., 2014). In fact, in many countries, the energy market is an open market and reservoir management rules are considered sensitive information by hydropower companies. Hence, reliable management data may not be publicly available, hindering the possibility of using reservoir operation modules in hydrological models. Moreover, the operation of the major hydropower plants now generally depends on energy price fluctuations, unlike in the past when it was a regulated sector (Gaudard et al., 2014; Massarutto and Pontoni, 2015).

This study aims at showing how machine learning methods can be used to improve hydrological models in alpine catchments that are highly affected by hydropeaking at the daily time scale. Machine learning methods have been widely applied in hydrology as a surrogate for distributed and semi-distributed models for various purposes, such as streamflow forecasting, sediment transport, flood prediction and many others (e.g., Raghavendra and Deka, 2014; Nourani et al., 2014; Rasouli et al., 2012; Solomatine and Shrestha, 2009). A peculiar characteristic of learning machine techniques is their ability to deduce the dynamic response of the system from available measured data. Several works highlight the use of machine learning methods as a valuable and accurate tool for modeling complex river basin systems in support of water management information needs (Karamouz et al., 2009; Khalil et al., 2005; Ticlavilca and Mckee, 2011).

In this short communication, we first performed a wavelet analysis of streamflow and energy price time series at the daily time scale for the Upper Adige catchment (North-East Italy), since the ecological relevance of hydropeaking in this river basin has been highlighted in several studies (Bruno et al., 2013; Zolezzi et al., 2009). The wavelet analysis is able to reveal the main mode of the frequency of a signal and identifies when any change in these modes occurs (Daubechies, 1990; Labat, 2005; Schaefli et al., 2007; Torrence and Compo, 1998). Moreover, using a wavelet coherence analysis (Grinsted et al., 2004) to investigate the impact of energy market fluctuations on river discharge, we identified the correlation between energy price and streamflow. Using a support vector machine (SVM), we coupled hydrological model results obtained with the Soil Water Assessment Tool (SWAT) with energy price time series and the day of the week to improve model prediction of hydropeaking on a daily time scale. Previous works (e.g., Torres-Rua et al., 2012) coupled physical models and machine learning to correct, for example, hydraulic simulation models. However, the combination between distributed or semi-distributed hydrological models and machine learning has rarely been attempted. In order to estimate the performance of our model, beside using traditional metrics like mean absolute error, mean absolute percentage error, root mean square error, ratio of root mean squared error to the standard deviation of observations and Nash-Sutcliffe efficiency, we propose to use the wavelet coherence between measured and modeled streamflow time series (Rathinasamy et al., 2014). This analysis allowed us to highlight at which temporal scales the coupled model outperformed the SWAT model calibrated without the reservoir management tool.

2. Methodology

2.1. Study area

The Upper Adige river basin is located in the North-East Italian Alps (Fig. 1) and has a drainage area of 6875 km^2 closed at Bronzolo. It is a typical alpine catchment with a large elevation range from 223 m a.s.l. to 3865 m a.s.l. The river basin is characterized by steep slopes and sharp hydroclimatic gradients (Callegari et al., 2015). The Upper Adige catchment is affected by a variety of stressors that affect its ecological status, hydropeaking being the most important one (Navarro-Ortega et al., 2015). Although several studies have focused on Upper Adige subcatchments (Mei et al., 2016b; Mei et al., 2014; Mei et al., 2016b; Penna et al., 2017a; Penna et al., 2014; Penna et al., 2017b; Tuo et al., 2016), few have tried to reproduce the hydrological behavior of the system including reservoir operation. Water discharge for hydropower production in the Upper Adige is managed with 15 artificial reservoirs, whose operational rules influence the measured discharge at the gauging station of Bronzolo. Reservoir management operational rules are not available and that is what motivated this research.

Land uses of the river basin are mainly forest, grassland and pasture, and barren land. The main soil types are loamy sand, silty clay, and sand. The data sets used to setup the SWAT model are the following:

- Digital elevation map (DEM) from Shuttle Radar Topography Mission (SRTM) produced by Consortium for Spatial Information (CGIAR-CSI), spatial resolution: 90 m × 90 m.
- Land use map: Corine Land Cover 2006 (CLC2006) from the European Environment Agency, spatial resolution: 100 m × 100 m.
- Soil map, developed by the Food and Agriculture Organization (FAO) of the United Nations.
- Digital stream network, EU-DEM product available at http://www.eea.europa.eu/data-and-maps/data/eu-dem.
- Daily precipitation and temperature data from a total of 65 rain gauges (60 rain gauges inside the basin and 5 rain gauges close to the basin boundary, see Fig. 1) were collected from the meteorological surveys of the Autonomous Province of Bolzano (data available at http://weather.provinz.bz.it/default.asp). Previous studies have shown that the sensitivity of hydrological models of the Upper Adige river basin depends on precipitation input (Duan et al., 2016; Mei et al., 2016a; Tuo et al., 2016), a topic that will not be further investigated in this work.

Daily measured streamflow data for the period at the Bronzolo gauging station (Fig. 1) were collected in the GLOBAQUA project (Chiogna et al., 2016). In this work, we considered the period November 1, 2004–October 31, 2010.

The river discharge time series measured at the Bronzolo gauging station is shown in Fig. 2A. Streamflow displays the typical features of an alpine catchment, with low winter flows and high flows during the melting period in spring and summer. Fig. 2B shows in more detail that river discharge fluctuates greatly during the winter period due to hydropeaking. Such fluctuations appear to be less pronounced during the high flow period.

2.2. Hydrological model

SWAT was developed by the Agricultural Research Service of the United States Department of Agriculture (Arnold et al., 2012; Neitsch et al., 2011). It can be used to simulate daily water cycles, crop growth, sediment, nutrient and pesticide transport in large river basins and