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Optimal floodgate operation for river flood management: The case study of Padova (Italy)

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ABSTRACT

Study region: A large, densely populated area nearby Padova (Veneto Region, Italy) is exposed to floods owing to the Brenta-Bacchiglione river network, which is formed by two main rivers and by a set of interconnected channels, control structures and pump stations.
Study focus: The Brenta and Bacchiglione rivers suffer from an increasing pressure in terms of flood events, especially for urban sprawl, anthropogenic modifications of drainage networks, and climate change. Finding and implementing effective remedies is hard in developed countries due to the presence of several constraints. Optimal flood management in complex river networks is then a way to reduce flood hazard, at a relatively low cost compared to structural measures. Hence, optimal operation rules for floodgates at an existing control structure are searched for to control the upstream water level and to divert a proper amount of the Bacchiglione discharge into the Brenta River. The operation rules have been endorsed by the Civil Engineering Department in charge of flood management and have been implemented in the flood forecasting Early Warning System of the Regional Civil Protection Office.
New hydrological insights: The proper operation of control structures allows reducing flood risk by balancing the water discharge in the river networks. The engagement of end-users proves beneficial as it fosters exchange of knowledge and allows for the effective adoption of research outcomes in decision making.

1. Introduction

River flooding is the most threatening natural hazard in Europe in terms of economic impact (EEA, 2010; Paprotny et al., 2018), and flood risk is expected to further increase in the near future (Arnell and Gosling, 2016; Dottori et al., 2018; Jongman, 2018; Ward et al., 2017). This can be ascribed to different factors as, for example, climatic change, sedimentation, anthropogenic modifications of soils, landscapes, and land use, socio-economic factors (Kundzewicz et al., 2014; Lane et al., 2007; Slater et al., 2015; Slater and Villarini, 2016; Viero et al., 2019; Winsemius et al., 2016). The situation is often exacerbated by a lack of maintenance of riverbeds, levees and hydraulic structures, which entails reduced discharge capacity and more frequent levee failures (Orlandini et al., 2015; Slater, 2016; Vacondio et al., 2016; Viero et al., 2013).

Effective adaptation strategies are needed (Jongman, 2018; Willner et al., 2018a,b), which comprise structural and non-structural measures. Non-structural measures could (and should) be pursued as complementary to structural measures or as a valuable alternative when structural river-flood protection measures are not convenient or feasible (Hino and Hall, 2017; Petry, 2002; Thieken

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et al., 2016; Ward et al., 2017). Non-structural measures to flood risk reduction comprise, for example, laws and regulations, economic instruments, efficient flood forecast-warning systems, flood risk assessment, awareness raising (Chen et al., 2019; Jamrussri and Toda, 2017; Kundzewicz, 2002), and also the optimal management of river networks (Yazdi and Salehi Neyshabouri, 2012).

A wealth of different approaches and models has been proposed to achieve "optimality" in flood defence planning and management. This is an active research field that includes the optimal design of river networks (Camnasio and Becciu, 2011; Guo et al., 2010; Housh, 2017; Wang and Huang, 2013, 2016; Woodward et al., 2014b), support to decision-making in flood management (Ahmad and Simonovic, 2006; Gu et al., 2014; Kong et al., 2019; Reimer and Wu, 2016; Soleimani-Alyar et al., 2016; Wang and Zhang, 2018; Woodward et al., 2014a), optimal operation of a multi-gate sluice structure considering different aspects of structure management (e.g., ecology, scour, gate vibrations and waterway navigation, see Erdbrink et al., 2014; Seifert and Moore, 2018), and multi-purpose optimization of reservoir management and operation (Celeste and Ventura, 2017; Chen et al., 2017; Chou and Wu, 2013, 2015; Haktanir et al., 2013; Jia et al., 2016; Ortiz-Partida et al., 2016; Meng et al., 2019). Optimization models have been applied also to determine policies for sustainable development and for planning of structural measures (Chitsaz and Banihabib, 2015; Chung et al., 2011; Eijgenraam et al., 2017; Nones, 2015).

The focus is here on the flood management in a complex river network. The case study is the the Brenta and Bacchiglione river network nearby (and through) the historical city of Padova (Veneto Region, Italy), which comprises several natural and man-made channels. The area has been subject to severe flooding in the past and in the recent years as well (Viero et al., 2013; Zanetti, 2013). Flood hazard is mainly due to the fact that the maximum conveyance capacity of the major rivers progressively reduces downstream of Padova (Martini et al., 2004); furthermore, the widespread presence of burrowing animals like the *Myocastor Coypus* (Sofia et al., 2017a; Viero et al., 2013) poses severe threats to the reliability of levees. In the recent years, the situation progressively worsened due to massive urbanization, anthropogenic modifications of drainage networks, and climate change (Alfieri et al., 2015, 2017, Blöschl et al., 2017, 2019; Mel et al., 2013; Miller and Hutchins, 2017; Pijl et al., 2018; Senatore et al., 2011; Sofia et al., 2014, 2017; Sofia and Tarolli, 2017). Importantly, flood-prone areas are densely populated and subject to intense industrial and agricultural activities (Roder et al., 2017).

The proper operation of sluice gates at an existing control structure, which allows diverting part of the Bacchiglione discharge into the Brenta River, can play a crucial role in balancing the 'discharge load' in the different branches of the Brenta-Bacchiglione river network downstream of Padova, thus reducing hydraulic hazard in a vast, highly-exposed area.

Optimization of the river network is achieved through the definition of specific operation rules that are the result of an off-line analysis. Such operation rules are *static*, in the sense that their real-time application (i.e., in the course of a flood event) is only based on the knowledge of simultaneous flow variables at different locations within the river network and does not require any model-based evaluation to achieve optimal flood control. The chance of pursuing such a simplified design is justified given the specific configuration of the problem at hand. Indeed, the control structure subject to optimization is located in the terminal part of the river course, where the duration of flood waves is relatively long, and effects associated to flow unsteadiness are negligible. Furthermore, static rules are easier to understand and put into practice for the non-scientific staff in charge of managing the control structures in the river network.

The definition of optimal operation rules has been pursued in accordance and cooperation with the Civil Engineering Department in charge of flood management in the Brenta-Bacchiglione river network; indeed, end-users engagement is important for the effective adoption of modelling analysis outcomes (Horne et al., 2016). Furthermore, these rules were implemented, using available features of the 2DEF two-dimensional hydrodynamic model, in the IMAGe Early Warning System that is operational at the Civil Protection Office in charge of flood forecasting, thus providing flood predictions that are coherent with the flood management actually performed.

2. Material and Methods

2.1. The Brenta-Bacchiglione river network nearby the city of Padova

The city of Padova is surrounded by two major rivers, named Brenta and Bacchiglione, and by a set of channels interconnected by a variety of control structures (Fig. 1).

The Brenta River, with a basin of about 1600 km^2, can convey more than 2500 m^3/s at the outlet of its mountain basin at Bassano del Grappa (about 60 km north of Padova). In the stretch between Bassano del Grappa and Padova, the Brenta River is wide and somewhere braided. Close to Padova, the Brenta River becomes narrower, as it is confined within relatively high artificial levees. North of the city centre, it receives water from the Muson dei Sassi River (basin of about 300 km^2, flow rates up to 100 m^3/s) and then it flows south-east reaching the Adriatic Sea near Brondolo, south of the Venice Lagoon. Downstream of Padova, the maximum discharge the Brenta River can convey reduces to about 1500 m^3/s (Martini et al., 2004).

The Bacchiglione River, with a basin of more than 1300 km^2 located in the pre-Alps north of the city of Vicenza (Mazzoleni et al., 2017; Viero, 2018), can convey a water discharge of up to 800 m^3/s at the south-east edge of the city of Padova. Before reaching Padova, the Bacchiglione River receives the flow form the Brentella Canal, dug in the 1314 and now used to divert part of the Brenta discharge into the Bacchiglione river during the dry season. At Padova, the Bacchiglione is divided into three courses:

- *Battaglia Canal*, dug in 1200 A.D. for drainage and navigation purposes, that flows south towards the Euganean hills;
- *Tronco Maestro* channel, the early course of the Bacchiglione River, that flows north and enters the historical centre of the city, and changes its name in *Piovego Canal* when it enters the city;
- *Scaricatore Canal*, dug in the late 1800 as flood channel, that flows east towards the Voltabarozzo Control Structure, where in turn

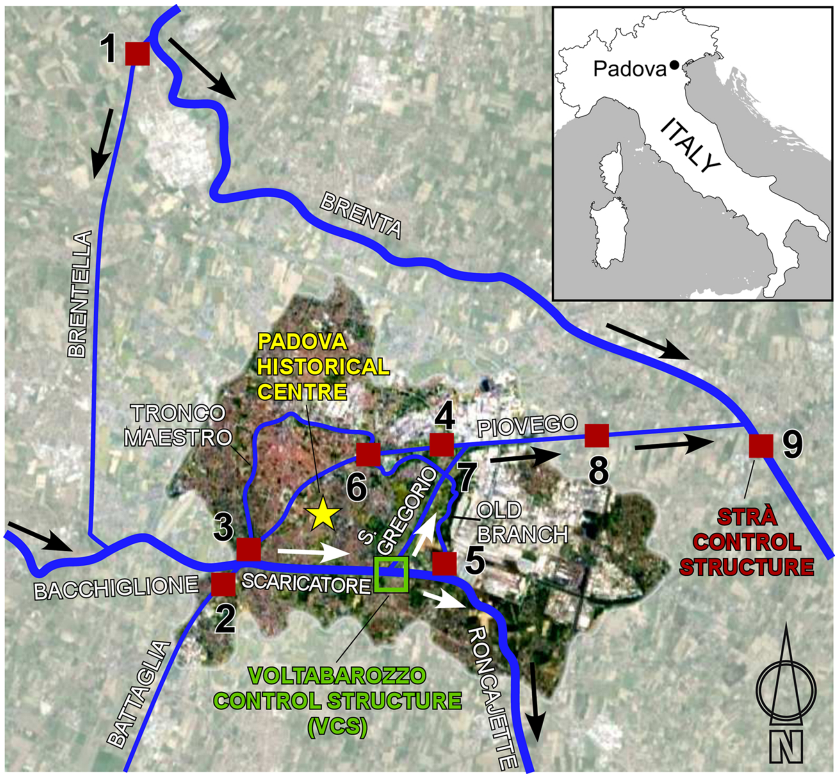

Fig. 1. Hydraulic network of Padova and the main hydraulic structures that control water levels and flow rates.

it is divided in the Roncajette River (actually the Bacchiglione main course downstream of Padova) and in the artificial S. Gregorio Canal.

The S. Gregorio Canal flows into the Piovego Canal and then in the Brenta River. Downstream of Padova, the Roncajette River flows south-east, collects the drainage waters of the Cagnola Channel, and finally merges with the Brenta River about 6 km upstream of the mouth in the Adriatic Sea.

Some historical notes. Until less than two centuries ago, the Bacchiglione River was still passing through the historic centre of Padova following a winding and relatively narrow path (Tronco Maestro in Fig. 1); downstream of Padova, it was flowing south-east with the name of Roncajette River. Unfortunately, the city was subject to frequent floods. In order to fix this issue, in 1830 the Austrian Government decided to build the 4 km long Scaricatore Canal, to keep the Bacchiglione floodwaters outside the city of Padova. The Scaricatore Canal is actually an artificial cutoff aimed at conveying the Bacchiglione discharge to the Roncajette River directly (Fig. 1). Due to an incorrect design, this canal was unable to convey the maximum flow rates of the Bacchiglione River during the disastrous flood occurred in 1882. Therefore, in the 1930s, according to the design of Luigi Gasparini, the Scaricatore Canal was enlarged and, from the Voltabarozzo Control Structure (green square in Fig. 1 ; see also Fig. 2), the new S. Gregorio Canal was dug with the aim of diverting part of the Bacchiglione floodwaters towards the last segment of the Piovego Canal and then to the Brenta River. In this way, hydraulic hazard was mitigated in both the city centre of Padova and downstream, along the course of the Roncajette River. Consider that, in times of low flow, water levels are kept constant at 12.0 m above the sea level (asl) for the Bacchiglione upstream of the Voltabarozzo Control Structure, and at 8.3 m asl for the Brenta River upstream of the Strà Control Structure (red square n. 9 in Fig. 1), through a proper operation of the sluice gates at the two control structures.

Current network operation during flood events. In the course of flood events, the secondary channels are disconnected from the primary network (i.e., the Brenta and Bacchiglione rivers). In particular, with reference to Fig. 1, gates are closed at the inlet of the Brentella Canal (1), of the Battaglia Canal (2), and of the Tronco Maestro channel (3); in addition, gates are closed at the outlet of the Piovego Channel just upstream of the S. Gregorio confluence (4) and at the confluence of the old branch of the Bacchiglione within the Roncajette River at Ca' Nordio (5). The S. Gregorio and Piovego canals thus perform as a unique flood canal, hereinafter denoted as SGP Canal.

The drainage of the city centre of Padova is guaranteed by the secondary channel network that, through the S. Massimo gates (6) conveys drainage waters south-east through the inverted siphon (7) under the S. Gregorio Canal towards the pumping station of Ca' Nordio (5), which allows pumping a flow rate of up to 40 m^3/s into the Roncajette River.

The tainter gates on the Piovego Canal at Noventa Padovana (8), which normally controls the water level in the whole city centre of Padova, are completely opened during flood events to facilitate discharging water from Bacchiglione to Brenta. Similarly, the sluice

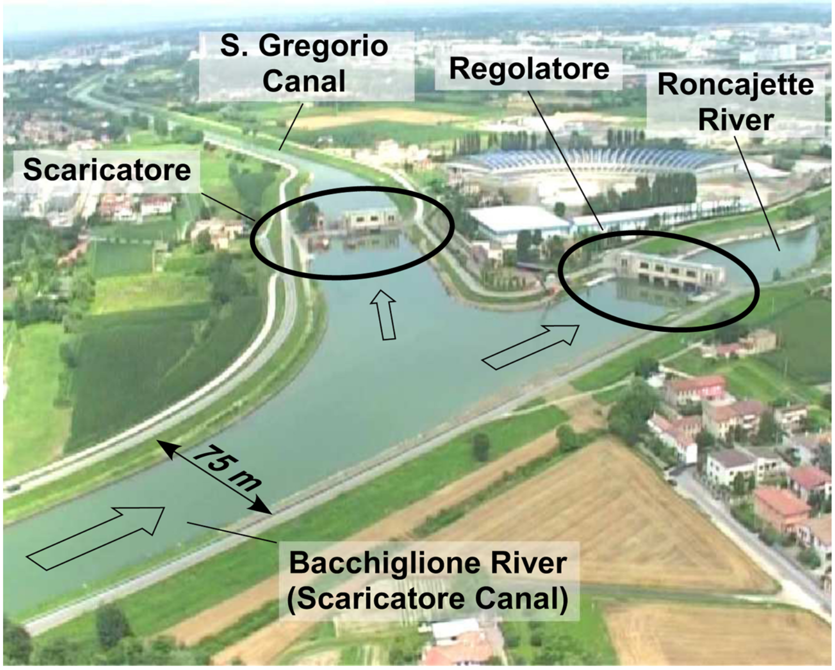

Fig. 2. Aerial view of the Voltabarozzo Control Structure (VCS), where the Scaricatore Canal divides into the Roncajette River and the S. Gregorio Canal. The Regolatore and Scaricatore facilities, with four and two sluice gates respectively, are also highlighted.

gates on the Brenta River at Strà (9), which normally controls the water level in the downstream segment of the Piovego Canal for navigation purposes, are completely open to limit backwater effects along the upstream Brenta River and, above all, in the Piovego Canal whose levees are relatively low.

The Voltabarozzo Control Structure. The Voltabarozzo Control Structure (denoted hereinafter as VCS) is a crucial element for flood management nearby and downstream of Padova. Indeed, it allows controlling the fraction of the Bacchiglione flow rate to be diverted through the S. Gregorio-Piovego (SGP) Canal toward the Brenta River, thus increasing the maximum conveyance of the Bacchiglione close to Padova and balancing the 'discharge load' in the Brenta and Bacchiglione rivers downstream of Padova.

The VCS is made up of two distinct multi-gate facilities (Fig. 2):

- the *Regolatore* is used to control the water level just upstream of the structure and the flow rate in the Roncajette River. It is equipped with four, 7.20 m wide, sluice gates that can be opened up to 6.75 m above the bottom level located at 5.70 m asl;
- the *Scaricatore* is used to divert part of the Bacchiglione flow rate into the SGP Canal toward the Brenta River. It is equipped with two, 7.20 m wide, sluice gates that can be opened up to 7.0 m above the same bottom level of 5.70 m asl;

The management of the six gates of the the VCS is actually manual, and is accomplished depending on the water levels measured just upstream and downstream of the control structure, and those of the Brenta River at Strà.

2.2. The 2DEF hydrodynamic model

In the present study, the simulation of flood events in the complex river and channel network described above is accomplished using the 2DEF hydrodynamic model (Defina, 2000, 2003; Viero et al., 2013). The model solves the full two-dimensional (2D) shallow water equations (SWEs) on unstructured triangular meshes. The 2DEF model enforces a statistical subgrid approach for bottom elevations (Defina et al., 1994; Defina, 2000), which allows for a physically based, accurate and stable treatment of wetting and drying processes on very irregular topographies (D'Alpaos and Defina, 2007). The SWEs are solved using a semi-implicit staggered finite-element method, based on a mixed Eulerian-Lagrangian approach (Defina, 2003). The depth-integrated horizontal dispersion stresses are evaluated using the Boussinesq approximation (Stansby, 2003), and the eddy viscosity is computed according to Uittenbogaard and van Vossen (2004). The 2DEF model has been improved in the years to simulate levee breaches (Viero et al., 2013), to account for interactions between free-surface flow and saturated flow in the topsoil layer (Viero et al., 2014), transport of pollutants and evaluation of transport time scales (Viero and Defina, 2016), anisotropy in bottom resistance due to oriented roughness (Viero and Valipour, 2017), and anisotropic effects due to buildings and obstacles in urban areas (Ferrari and Viero, 2020; Viero, 2019). The model also allows coupling 2D elements with 1D channels, the latter being used to model the flow in regular 1D river reaches and within the minor channel network. A set of specific 1D-links allows modelling possible overtopping of levees, the

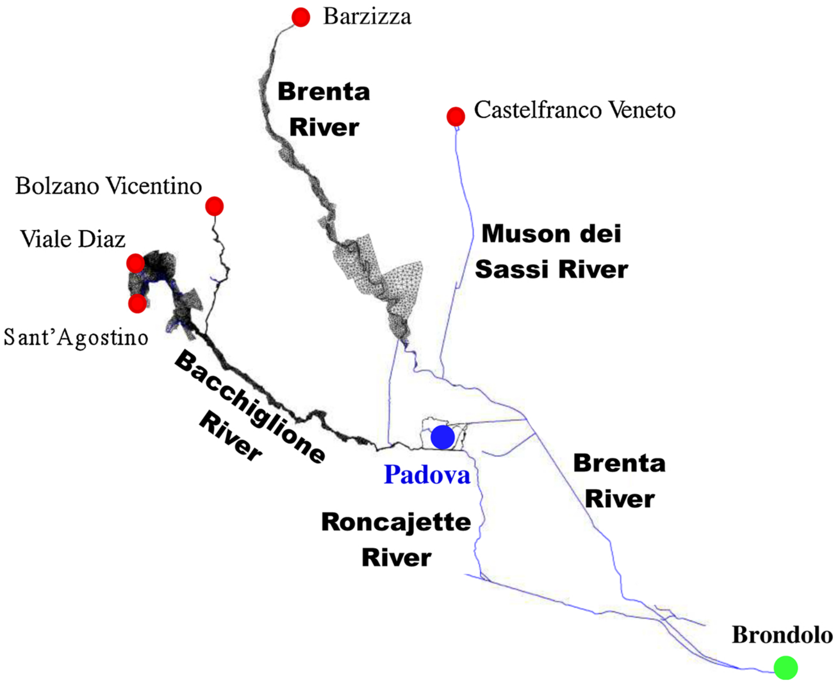

Fig. 3. Computational mesh used to model flood propagation in the Brenta-Bacchiglione river network. Red points denote inflow boundary conditions; the green point locates the Brenta mouth in the Adriatic Sea at Brondolo.

presence of sills, and the operations of hydraulic facilities and devices such as gated flow controls and pump stations (D'Alpaos and Defina, 2007; Martini et al., 2004; Viero et al., 2013; Viero and Defina, 2017, 2019).

2.3. Model set-up for the Brenta-Bacchiglione river network

A computational mesh was set-up to describe the study area (Fig. 3). The model includes the Tesina River from Bolzano Vicentino, the Retrone River from S. Agostino, the Bacchiglione River from Viale Diaz (north of the city center of Vicenza), the Brenta River from Barzizza (north of the historical town of Bassano del Grappa), and the Muson dei Sassi River from Castelfranco Veneto. All these watercourses can be seen as tributaries of Brenta River, which flows into the Adriatic Sea near Brondolo, south of the Venice Lagoon (Fig. 3). The model includes some external flood-prone areas, such as the city of Vicenza along the Bacchiglione River and some floodplains along the Brenta River, north of Padova.

The mesh geometry and topography were set-up using aerial images and data from LIDAR and Multi-Beam surveys, technical maps and cross-sections (`www.pcn.minambiente.it/mattm` and `https://idt2.regione.veneto.it`). We paid particular attention to pick the correct elevations of levees and to include in the model the different hydraulic structures properly.

The domain is discretized with about 30000 2D triangular elements and 24000 nodes, 2600 1D-channel elements, and 5300 1D-links. 1D-channel elements are used to model straight river reaches with simple (i.e., not compound) sections and to account for the presence of small channels dissecting the urban and rural areas, which play an important role on the propagation of flood waves over initially dry areas. Most of the 1D-links are used to model levees and embankments that, in case of overflowing, are expected to force sub- to super-critical transition (i.e., critical condition); other 1D-links are deputed to model sluice gates and pump stations.

The model was calibrated and tested by simulating the most severe flood events occurred in the years 2009-2014, for a total of 5 flood events. As boundary conditions, we prescribed hourly flow rates recorded at the upstream cross-sections (at Bolzano Vicentino, Viale Diaz, S. Agostino, Barzizza and Castelfranco Veneto) and water levels of the Adriatic Sea measured close to Brondolo (Mel and Lionello, 2016). Measured data were provided by the Regional Agency for Environmental Protection of the Veneto Region (ARPAV), which maintains a network of several gauging stations for water levels and flow rates within the basin. Flow rates discharged within the main rivers by the pumping stations of the external drainage network were provided by the land reclamation authority Brenta-Bacchiglione; sea levels were provided by Centro Previsioni e Segnalazioni Maree of the Venice Municipality.

In simulating past flood events for model calibration and testing, we force the model to reproduce the actual discharge partitioning performed at the VCS, according to the gate operations performed (and recorded) by the Civil Engineering Department in charge of the gate management. The model is calibrated by trial and errors to obtain a suitable set of roughness coefficients for the different river reaches and zones (i.e., riverbeds, banks, floodplains, etc.), for a total of 40 model parameters.

The accuracy of the model was then checked by comparing the model results with time series of water levels measured at eight gauging stations located along the course of the Brenta and Bacchiglione rivers, and against point measurements of discharge performed by ARPAV using an Acoustic Doppler Current Profiler (ADCP) in the course of most of the considered flood events (ADCP measurements were carried out at downstream sections of the rivers, where flow velocity is within the operating range of the instrument). Model errors in terms of water levels at the flood peak are generally lower than 20 cm at all the gauging stations; the maximum relative error in terms of discharges is 8%.

We took great care to maximize the model robustness and accuracy, as well as to optimize the mesh to reduce simulation times, as the 2DEF model impementation described herein is the hydrodynamic core of the IMAGe flood forecasting and Early Warning System operational at the Centro Funzionale Decentrato (CFD) of the Veneto Region, the public office in charge of flood forecasting (Crestani et al., 2018; Mel et al., 2018; Ronco et al., 2016).

2.4. The IMAGe Early Warning System for the Brenta-Bacchiglione rivers

As already anticipated, the above implementation of the 2DEF hydrodynamic model is part of a Flood Forecasting and Early Warning System (EWS) developed since 2015 for the CFD office of the Veneto Region and named IMAGe (Interface and Model for the Alert and manaGement of flood events). The need of an effective EWS for the Brenta-Bacchiglione river basin became apparent after the severe flood occurred in 2010 (Viero et al., 2013), to allow for an improved management of flood events and civil protection activities.

The IMAGe EWS allows *i)* importing and pre-processing hydro-meteo-climatic data from the network of gauging stations operated by the Agency for Environmental Protection of the Veneto Region (ARPAV) and from the numerical weather prediction model COSMO-5 (Voudouri et al., 2018); *ii)* running the hydrological model and visualizing the predicted discharge hydrographs at the outlet of the mountain basis; *iii)* running the hydrodynamic model and analysing water depth, flow rate and velocity within the river network and in the (possibly) flooded areas; *iv)* producing summary and detailed reports for the involved authorities on exceeding alert levels and on water level time series.

The semi-distributed, geomorphological hydrological model (Rinaldo et al., 2015; Benettin et al., 2015, 2019) estimates the temporal evolution of soil moisture content, runoff and outflow dynamics in the mountain basins of the Bacchiglione and the Brenta rivers. The spatial and temporal dynamics of meteorological forcing, including precipitation fields, is evaluated using spatial geostatistical interpolation (via Kriging techniques) of observed data series. The rainfall fraction actually involved in the generation of flood waves is based on suitable water balance equations (Benettin et al., 2013). The river basins are divided into sub-catchments, for which vegetated and urban (impervious) fractions are evaluated from remote sensing data and simulated separately. In the vegetated fraction, infiltration to the root zone is split into evapotranspiration, subsurface flow and groundwater recharge. In the urban areas, all the incoming rainfall is assumed to produce runoff, but an initial fraction of the total runoff is diverted to water treatment plants. For every reach and at the outlet of the basins, the hydrologic response is computed using the convolution between the spatial and temporal distribution of the effective rainfall and the geomorphologic instantaneous unit hydrograph (Rinaldo and Rodriguez-Iturbe, 1996; Rinaldo et al., 2006), which depends on the distributions of the residence times in the different flow paths of the basin. The calibration parameters of the hydrological model can be subdivided into three categories: *i)* parameters related to soil properties and runoff production, *ii)* dynamical parameters related to transport processes within hillslopes and channels, and *iii)* vegetation parameters that define evapotranspiration rates and long-term soil-atmosphere interactions. The calibration set of model parameters is computed using a Markov chain Monte Carlo approach (Vrugt et al., 2009), to obtain the best fit between modelled and measured discharge time series at the basin outlets and at inner gauged sections as well. For example, the model for the Bacchiglione basin at Viale Diaz (Fig. 3) has been calibrated from September 2010 to December 2015. For the entire calibration period, the Nash-Sutcliffe Efficiency (*NSE*) is up to 0.96 and the Root Mean Square Error (*RMSE*) is 5.2 m^3/s; $NSE = 0.95$ and $RMSE = 8.3$ m^3/s for flow rates greater than 20 m^3/s (12% probability of exceedance); $NSE = 0.78$ and $RMSE = 23.1$ for flow rates greater than 100 m^3/s (1% probability of exceedance) (Passadore et al., 2018).

The discharge hydrographs predicted by the hydrological model are then provided, as inflow boundary conditions, to the 2DEF hydrodynamic model that simulates the propagation of flood waves in the river network and, in case of overflowing, the flooding of adjacent areas.

3. Definition of optimal operation rules for the Voltabarozzo Control Structure

3.1. Premises

It has first to be noted that the discharge along the SGP Canal, Q_{SGP}, depends on the opening of the Scaricatore gates, on the upstream water level, and on the flow rate in the Brenta River at Strà that determines the downstream water level for the SGP Canal. Furthermore, the levees of the Piovego Canal are relatively low and, in case of high downstream levels, Q_{SGP} must be further limited to avoid overflowing and possible levee failures along the downstream reach of the Piovego Canal.

As a first step, the hydrodynamic model has been used to evaluate the importance of unsteady effects on the propagation of flood waves within the considered channel networks. It is known, in fact, that accounting for hydraulic interactions in complex river systems remains an open challenge for systemic flood risk management, in particular when flow unsteadiness plays a crucial role (Ciullo et al., 2019; Di Baldassarre et al., 2009). Fortunately, the typical duration of flood wave along the Brenta and Bacchiglione rivers at Padova is long compared to the transit time in the downstream branches. This makes unsteady effects negligible in the management of the VCS.

Then, the hydrodynamic model has been used to compute, under steady flow conditions, the maximum flow rate that the SGP can

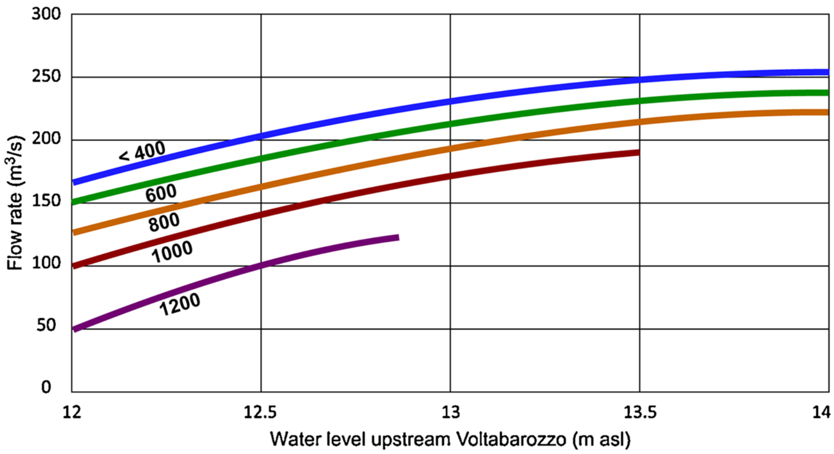

Fig. 4. Maximum flow rate that can be conveyed by the SGP Canal into the Brenta River (i.e., with the Scaricatore gates completely open) as a function of the water level upstream of the VCS; different lines refer to different flow rates in the Brenta River upstream of the Piovego confluence, $Q_{\mathrm{Bre}}^{\mathrm{ups}}$.

discharge into the Brenta River (i.e., with the Scaricatore gates completely open and avoiding levee overflowing), as a function of the water level upstream of the VCS and of the flow rates in the Brenta River upstream of the Piovego confluence, $Q_{\mathrm{Bre}}^{\mathrm{ups}}$ (Fig. 4). On the one hand, the discharge divertable through the SGP Canal, Q_{SGP}, can be increased by increasing the water level upstream of the VCS, h_{ups}, which entails, on the other hand, reducing the levee freeboard along the Scaricatore Canal. In addition, due to backwater effects, the maximum divertable discharge reduces for increasing $Q_{\mathrm{Bre}}^{\mathrm{ups}}$.

Thanks to the joint operation of the Regolatore and the Scaricatore facilities, water levels upstream of the VCS can be modified (to some extent, and compatibly with levee elevations) also for fixed flow rate values. This gives additional flexibility to the entire control system if compared with the case of lateral floodgates only.

With this in mind, the goal is to define a set of optimal operation rules for the VCS to minimize the flood risk for both the city of Padova and the downstream flood-prone areas.

3.2. Minimization of flood risk

We started by observing that the flood risk in the whole system is minimum when it is equally distributed in the different branches of the channel network (and in the adjacent areas). By analysing the maximum discharge capacity in the different reaches of the channel network using the 2DEF hydrodynamic model, and according to the Civil Engineering Department in charge of flood management, five risk classes have been defined (Fig. 5). Each risk class corresponds to a specific range of four variables:

1. the flow rate in the Roncajette River, Q_{Ron}, to account for the flood hazard in the Roncajette River and on the adjacent areas;
2. the flow rate in the Brenta River downstream of the Piovego confluence, $Q_{\mathrm{Bre}}^{\mathrm{dwns}} = Q_{\mathrm{Bre}}^{\mathrm{ups}} + Q_{\mathrm{SGP}}$, to account for flood hazard in its lower reach and on the adjacent areas;
3. the water level upstream of the VCS, h_{ups}, to account for flood hazard along the Scaricatore Canal and on the adjacent areas;
4. the minimum levee freeboard along the SGP Canal, to account for flood hazard along the canal and on the adjacent areas.

Note that, for the SGP Canal, the levee-freeboard is used in place of the flow rate, as here the relationship between level and discharge is not a one-to-one function due to the variable downstream water level (that depends on the Brenta flow rate).

Based on how the classes have been determined, it can be assumed that, for a given risk class, flood risk is reasonably equivalent in all the parts of the system. Indeed, the definition of such risk classes is made by accounting for the risk of overflowing in the different branches of the principal channel network, and also for exposure and vulnerability in the adjacent areas.

Given the scope of the present study, exposure, vulnerability and, in turn, hydraulic risk in areas adjacent to the river network were not evaluated according to a rigorous, quantitative procedure. Besides the results provided by the hydrodynamic models in terms of levee freeboard, we relied on qualitative, expert-based evaluations (i.e., technicians of the Civil Engineering Department) to account for the quantity and quality of exposed assets, their vulnerability, and the probability of levee failures. We believe that expert-based considerations are appropriate for the specific case study, because levee failures driven by piping cannot be predicted deterministically (D'Oria et al., 2019; Mazzoleni et al., 2014; Michelazzo et al., 2018), and the presence of animal burrows is becoming increasingly important (Orlandini et al., 2015; Palladino et al., 2020; Viero et al., 2013). It is also known that economic implications of flood risk go beyond the direct damages that are typically considered, and a thorough quantitative assessment is still an open challenge (Koks, 2018; Koks et al., 2019; Norén et al., 2016).

RISK CLASSES	1	2	3	4	5
RONCAJETTE FLOW RATE Q_{Ron} (m³/s)	⩽ 100	101 - 200	201 - 350	351 - 500	> 500
UPSTREAM LEVEL at VOLTABAROZZO h_{ups} (m asl)	12.00	12.01 - 13.00	13.01 - 13.50	13.51 - 14.00	> 14.00
BRENTA FLOW RATE Q_{Bre}^{dwns} (m³/s)	⩽ 400	401 - 800	801 - 1200	1201- 1400	> 1400
MINIMUM FREEBOARD along the SGP Canal (m)	1	1	0.5	0.5	0.5

Fig. 5. Definition of the five risk classes with the specific range of: flow rate in the Roncajette River, Q_{Ron}; water level upstream of the VCS, h_{ups}; flow rate in the Brenta River downstream of the Piovego confluence, $Q_{\mathrm{Bre}}^{\mathrm{dwns}}$; minimum levee freeboard along the SGP Canal.

3.3. Determining optimal operation rules

The optimization of the system to achieve minimum flood risk consists in managing the sluice gates so as to remain within the lowest possible risk class. To this purpose, we designed a specific algorithm that, at a given time step, determines the opening of the six gates of the VCS to minimize flood risk based on water levels and discharges at specific locations within the river network, which can be identified as *known variables*.

At each time step, the *known variables* are the discharges flowing in the Bacchiglione River, Q_{Bac}, and in the Brenta River upstream of the Piovego confluence, $Q_{\mathrm{Bre}}^{\mathrm{ups}}$, whereas the discharges in the Roncajette River and in the SGP Canal (Q_{Ron} and Q_{SGP}, respectively), the water level upstream of the VCS, h_{ups}, and the minimum levee freeboard along the SGP Canal are *free variables* that depend on the gate operations. Mass conservation at confluences entails $Q_{Bac} = Q_{Ron} + Q_{SGP}$ and $Q_{\mathrm{Bre}}^{\mathrm{dwns}} = Q_{\mathrm{Bre}}^{\mathrm{ups}} + Q_{\mathrm{SGP}}$.

In the exploratory phase of the study, the algorithm is coupled with the 2DEF hydrodynamic model to test its effectiveness through the simulation of past flood events. Chosen a time step of one hour for the simulations (a sensitivity analysis did not show any advantage associated with using smaller time steps), the algorithm determines the gate opening of VCS based on *known variables* that, in this case, are computed by the 2DEF model; then it drives the 2DEF model to simulate flood propagation with the prescribed gate opening until the next time step. The use of a calibrated hydrodynamic model assures that the obtained solution, in terms of *free variables*, is plausible.

In designing the operation of the VCS, two different relevant cases can be identified:

1. For $Q_{Bac} \leq 100$ m^3/s, the Scaricatore gates are kept closed according to the previous management of the VCS. The Regolatore gates are operated to keep the upstream water level, h_{ups}, equal to 12 m asl.
2. For $Q_{Bac} > 100$ m^3/s, the Scaricatore gates should be (partially) opened to achieve flood risk minimization. In this case, the algorithm first attempts to recover the lower risk class in terms of Q_{Ron} by discharging the excess flow through the SGP Canal toward the Brenta River, while keeping h_{ups} and $Q_{\mathrm{Bre}}^{\mathrm{dwns}}$ within the same risk class (Fig. 4).
   In general, within a given risk class, the flow rate through the Roncajette River, Q_{Ron}, is given the maximum value (within the class range) so as to minimize the upstream water level, h_{ups}, and the total discharge in the downstream reach of the Brenta River, $Q_{\mathrm{Bre}}^{\mathrm{dwns}}$.
   The last control concerns the minimum levee freeboard along the SGP Canal. If a freeboard is out of range, the algorithm determines the needed closure of the Scaricatore gates.
   If it is not possible to keep the three *free variables* within the same risk class, the algorithm assumes for Q_{Ron} the value associated to the higher risk class.

A summary of the operation rules for the gates of the VCS, for an increasing discharge of the Bacchiglione River, is shown in Fig. 6. As previously described, when the algorithm cannot keep all the *free variables* within the same risk class, the flow rate in the Roncajette River is increased first.

An example of VCS management is shown in Fig. 7, for the rising limb of a typical flood wave in the Bacchiglione River (blue line). As long as the Bacchiglione flow rate, Q_{Bac}, is lower than the 100 m^3/s threshold (risk class #1, light blue), the upstream water level, h_{ups}, is 12.00 m asl and the Scaricatore gates remain closed ($Q_{SGP} = 0$). Once Q_{Bac} exceeds the 100 m^3/s threshold (risk class #2, green), the Scaricatore gates open to maintain Q_{Ron} fixed at 100 m^3/s and $h_{ups} = 12.00$ m asl; Q_{SGP} increases accordingly. When this is no longer possible because of the increase of Q_{Bac}, Q_{Ron} is allowed to rise up to 200 m^3/s. Once Q_{Ron} exceeds 200 m^3/s (risk class #3, yellow), first h_{ups} rises up to 13.00 m asl, then Q_{Ron} increases up to 350 m^3/s. At this point, h_{ups} rises again, up to 13.50 m asl, and Q_{Ron} up to 500 m^3/s (risk class #4, orange). Finally, h_{ups} can increase up to 14 m asl, reaching the maximum flow rate divertable through the SGP Canal, Q_{SGP}, and the exceeding flow rate is totally discharged into the Roncajette River ($Q_{Ron} > 500$ m^3/s, risk class #5, red).

The effectiveness of the operation rules has been tested by simulating the whole year 2009, during which some relevant flood

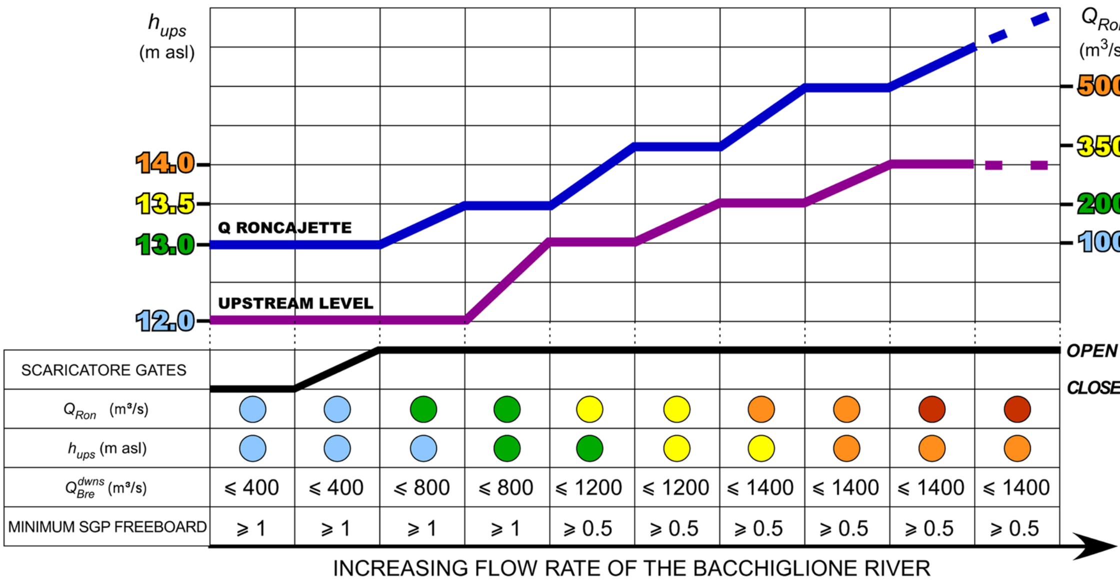

Fig. 6. Management of the VCS for increasing flow rates in the Bacchiglione River.

events occurred. The algorithm succeeded in determining the gate opening along the entire the simulated period, such that all the variables of interest fully satisfy the management criteria summarized in Figs. 5 and 6 .

Figure 8 shows the management of the VCS for the flood event occurred between 28/4/2009 and 1/5/2009, when the flow rates of the Brenta and the Bacchiglione rivers upstream of the city of Padova exceeded 650 m^3/s and 350 m^3/s, respectively. Interestingly, in this case the flow rate diverted through the SGP Canal, Q_{SGP}, was limited by the large flow rate of the Brenta River (Q_{Bre}^{dwns} = 800 m^3/s, risk class #2). As a consequence, it was not possible to increase the water level upstream of Voltabarozzo intentionally to further increase Q_{SGP}; hence, during this flood event, h_{ups} remained fixed at 12.00 m asl, even at the flood peak in the Roncajette River.

4. Implementation of the operation rules in the IMAGe EWS

The final goal of the present study was to implement the optimal operation rules in the IMAGe Early Warning System described in Sect. 2.4, so as to simulate the management of the VCS correctly in real-time flood forecast.

Taking advantage of the *static* nature of the operation rules for the VCS, we used specific 1D-links implemented in the 2DEF

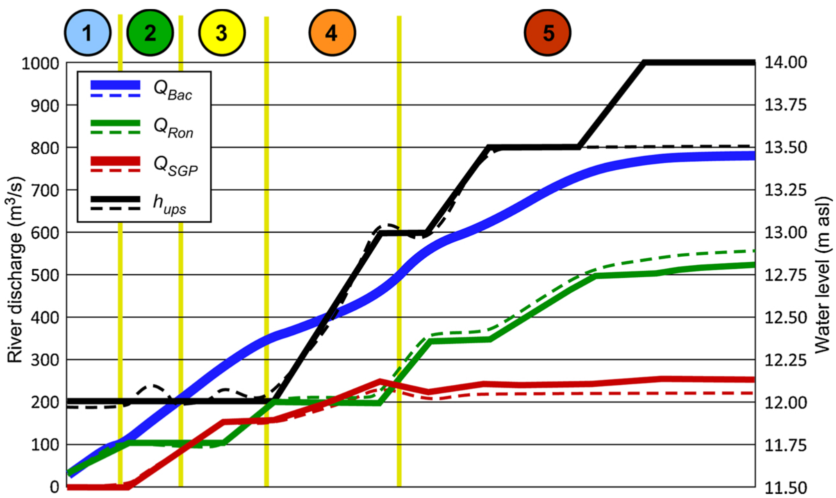

Fig. 7. Example of management of the VCS for a flow rate of 400 m^3/s in the Brenta River upstream of the Piovego confluence. Thick lines refer to the operation rules described in Sect. 3.3, whereas dashed lines have been obtained using the simplified version of the operation rules implemented into the IMAGe EWS (see Sects. 2.4 and 4).

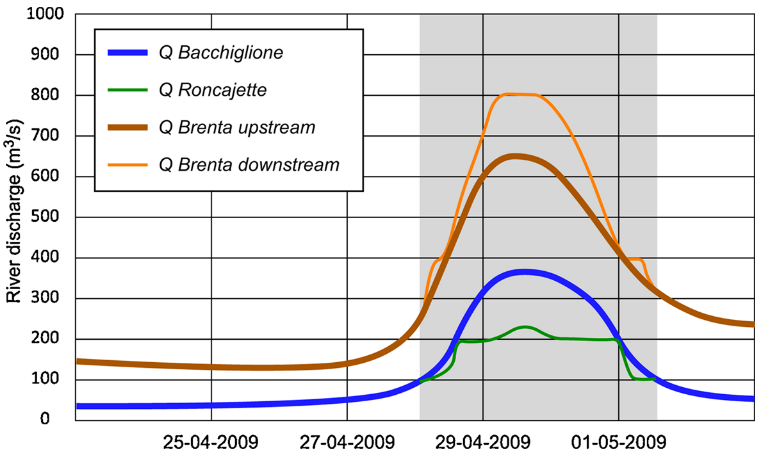

Fig. 8. Management of the VCS applied to the major flood event of 2009, occurred between 28/04 and 1/05. The shaded area denotes the time interval in which the Scaricatore gates are open.

hydrodynamic model to reproduce the gate operations described in Sect. 3.3 directly (i.e., without using any external algorithm).

Specifically, in the 2DEF model, we modelled each sluice gate using an available type of 1D-link, which operates the gate to maintain a prescribed upstream water level (i.e., a target level). The two sluice gates of the Scaricatore were given a target level of 12.00 m asl, so that they remain close for $h_{ups} \leq 12.00$ and progressively open for $h_{ups} > 12.00$ m asl. For the Regolatore gates, a target level of 11.95 m asl was assigned to the first gate and its width selected so that a discharge of 100 m^3/s determines an upstream level of 12 m asl with the gate completely open. In this way, when the first discharge threshold $Q_{Ron} = 100$ m^3/s is reached, $h_{ups} = 12.00$ m asl, and the Scaricatore gates start to open, thus diverting the exceeding discharge to the SGP Canal. For a further increase of Q_{Bac}, h_{ups} increase as well, thus determining the opening of the second Regolatore gate, whose target level was set to 12.05 m asl, and so on. Obviously, the width of each gate of the Regolatore facility was modified, with respect to the actual width, without changing the total width of the four sluice gates.

The additional controls concerning the minimum levee freeboard along the SGP Canal and the maximum discharge within the downstream reach of the Brenta River were implemented by connecting in series two fictitious gates downstream of the two Scaricatore gates. These fictitious gates close progressively when target levels are reached along the SGP Canal and the Brenta River, thus limiting Q_{SGP} in order to keep $Q_{\mathrm{Bre}}^{\mathrm{dwns}}$ and the minimum freeboard within the range of the associated risk class.

The model set-up implemented within the IMAGe EWS produces almost the same results as the procedure described in Sect. 3.3, as shown in Fig. 7 where dashed lines refer to the simplified IMAGe implementation of the operation rules. The IMAGe implementation have been verified thoroughly by simulating 26 flood events occurred between 2010 and 2014 (Table 1). In simulating these flood events, the IMAGe EWS was forced using measured rainfall and meteorological data.

Figures from 9 to 12 show the model results for 4 significant flood events, characterized by increasing intensity, and which cover different sorts of gate operations. A detailed description of the specific operations rules applied in each case is reported in the figure captions. The procedure implemented in the EWS shows two slight deviations with respect to the algorithm described in Sect. 3.3: the former is described in the caption of Fig. 10, the latter in the caption of Fig. 12. Yet, the difference in terms of discharge partitioning is negligible.

5. Conclusions

This research focuses on optimizing the operation of the hydraulic network of the city of Padova and, in particular, of the Voltabarozzo Control Structure which allows diverting waters from the Bacchiglione River to the Brenta River.

The operation rules allow determining the flow rate to be diverted and the water level upstream of the Voltabarozzo Control Structure as a function of simultaneous values of discharge flowing in the Bacchiglione and Brenta rivers. The principle behind flood management is the minimization of hydraulic risk, which consists in distributing the risk in the different parts of the hydraulic network equally. The goal is achieved by defining five risk classes accounting for hydraulic load at various locations along the reaches, and for hydraulic hazard, exposure and vulnerability of assets in the adjacent, flood-prone areas. For each risk class, a specific range is defined for discharges and minimum levee freeboard in the main branches of the channel network.

The operation rules have been tested by simulating several recent flood events. Furthermore, they have been implemented in the IMAGe Early Warning System, which is operational at the Regional Office in charge of flood forecasting, to provide accurate real-time predictions of discharges, water levels, levee freeboard, and possible flooding along the Brenta-Bacchiglione river network and over the adjacent areas.

The present work was developed in collaboration with the local Civil Engineering Department in charge of flood management, so as to take advantage of the direct knowledge of the technicians in charge of flood management, as well as to create trust in the result of the work by those who have to put into practice the management rules.

Table 1
List of the events of the period 2010-2014 we selected for verifying the sluice gates modelling into the EWS integrate platform. Each event is characterized by a flow rate entering the node, Q_{Bac}^{MAX}, greater than 100 m^3/s, a threshold that produces the opening of the Scaricatore gates. The flood events reported in Sect. 4 are highlighted in italics; the events in which the diverted discharge, Q_{SGP}, is limited because of the high Brenta discharge are in bold font.

n.	begin	end	Q_{Bac}^{MAX}	n.	begin	end	Q_{Bac}^{MAX}
1	4 May 2010	10 May 2010	200	*14*	*11 Nov 2012*	*15 Nov 2012*	*500*
2	25 Sep 2010	27 Sep 2010	150	15	28 Nov 2012	3 Dec 2012	300
3	25 Oct 2010	27 Oct 2010	270	**16**	**16 May 2013**	**22 May 2013**	**500**
4	*31 Oct 2010*	*12 Nov 2010*	*670*	17	24 May 2013	27 May 2013	140
5	16 Nov 2010	21 Nov 2010	300	18	25 Dec 2013	28 Dec 2013	240
6	21 Nov 2010	26 Nov 2010	210	19	4 Jan 2013	8 Jan 2013	170
7	*22 Dec 2010*	*31 Dec 2010*	*390*	20	18 Jan 2014	23 Jan 2014	250
8	16 Mar 2011	22 Mar 2011	260	**21**	**31 Jan 2014**	**11 Feb 2014**	**330**
9	26 Oct 2011	27 Oct 2011	130	22	1 Mar 2014	07 Mar 2014	160
10	***6 Nov 2011***	***11 Nov 2011***	***310***	23	21 Jul 2014	25 Jul 2014	105
11	21 May 2012	22 May 2012	130	24	5 Nov 2014	10 Nov 2014	320
12	31 Oct 2012	1 Nov 2012	140	25	10 Nov 2014	15 Nov 2014	180
13	01 Nov 2012	5 Nov 2012	180	26	15 Nov 2014	21 Nov 2014	230

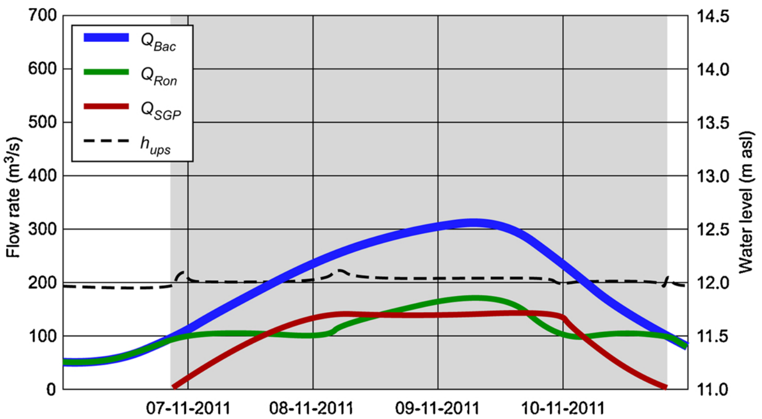

Fig. 9. Flood event of 6-11 November 2011. The shaded area denotes the time interval in which the Scaricatore gates are open. The basic operation rules in this event are analogous to those described in Figs. 7 and 8 .

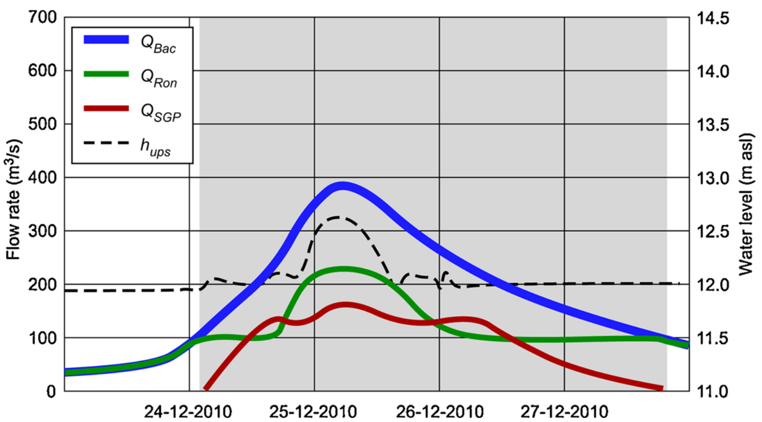

Fig. 10. Flood event of 22-27 December 2010. The shaded area denotes the time interval in which the Scaricatore gates are open. The Bacchiglione flow rate, Q_{Bac}, produces an increase of the upstream level, h_{ups}, up to 12.60 m asl in order to increase the flow rate discharged through the SGP Canal, Q_{SGP}. The rise of h_{ups} also entails a slight increase of the flow rate in the Roncajette River, Q_{Ron}, up to a maximum of almost 215 m^3/s. Here, the simplified implementation in the IMAGe EWS performs slightly different than the operation rules defined in Sect. 3.3, which would have limited Q_{Ron} to 200 m^3/s.

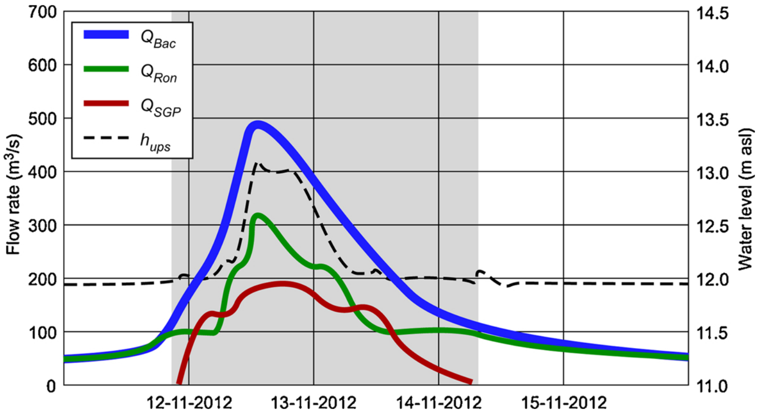

Fig. 11. Flood event of 11-16 November 2012. The shaded area denotes the time interval in which the Scaricatore gates are open. After Q_{Ron} reached 200 m^3/s, the upstream level, h_{ups}, is risen up to almost 13.00 m asl so as to increase Q_{SGP}, with Q_{Ron} fixed at about 200 m^3/s. Once h_{ups} tends to exceed 13.00 m asl, the third Regolatore gate opens to further increase Q_{Ron}, up to a maximum of 350 m^3/s, keeping the water level at the node, h_{ups}, at about 13.00 m asl.

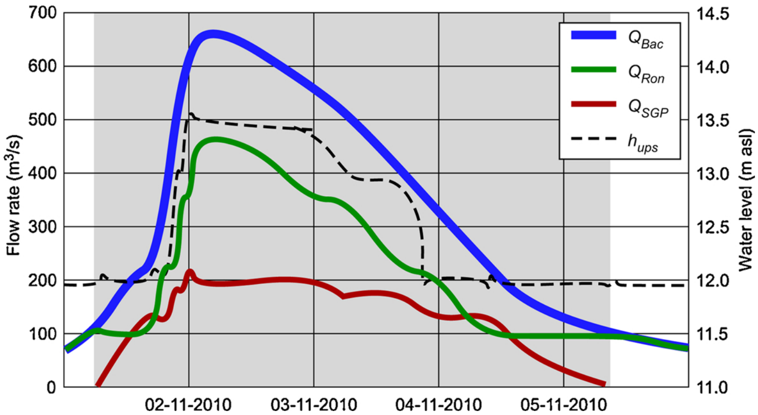

Fig. 12. Flood event of 31 October - 5 November 2010. The shaded area denotes the time interval in which the Scaricatore gates are open. In this event, the maximum value of Q_{Bac} exceeds 500 m^3/s. Once Q_{Ron} reaches 200 m^3/s, first the upstream water level h_{ups} rises up to 13.00 m asl, then the third Regolatore gate opens to further increase Q_{Ron} up to 350 m^3/s. At this point, h_{ups} rises again, up to 13.50 m asl, allowing Q_{SGP} to increase up to a maximum of about 200 m^3/s. Then, the fourth Regolatore gate opens to discharge the exceeding flow rate into the Roncajette River. This is the second slight difference with respect to the rules defined in Sect. 3.3, which would impose a further increase of h_{ups} up to 14.00 m asl (Figs. , and 8). The effect, in terms of increasing Q_{SGP}, is practically negligible (Fig. 4).

We highlight that the operation rules described herein refer to the current configuration of the river and channel network. In case of improvements of the hydraulic network, as for example levee heightening, the risk classes should be re-defined to account for the modified (reduced) risk. Similarly, in case of emergency situations or sudden accidents such as a levee collapse (e.g., the levee breach formed in the Roncajette River during the November 2010 flood event, Viero et al., 2013), the management of the Voltabarozzo Control Structure should adapt to the particular situation in order to minimize the discharge load in the damaged branch of the network (e.g., Yang et al., 2020).

Further applications of the 2DEF hydrodynamic model, with optimal operation of the Voltabarozzo Control Structure, should aim at evaluating the effects of additional interventions, such as levee rise in the most critical segments of the channel network, and the construction of the Padova-Venezia waterway to be used, beside navigation, to divert part of the Brenta River, from downstream of Strà, directly to the Venice Lagoon (Martini et al., 2004; Mel et al., 2019, 2020).

The proposed approach, which uses hydrodynamic modelling and expert-based knowledge to determine an equal distribution of flood risk in a river network, allows minimizing flood risk through optimal operation of existing control structures, without significant additional costs. The suggested approach can be adapted and applied to different contexts, accounting for the peculiarities of each specific river network but keeping the basic principles unchanged. Finally, we remark the importance of collaborating with public institutions and with the technicians in charge of managing the river networks, to promote exchange of knowledge and expertise, and to maximize the practical impact of scientific research.

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Author statement

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Appendix A. Supplementary Data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ejrh.2020.100702.

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