1. Introduction

[2] Ecologists and hydrologists have long recognized that streamflow regimes are major drivers of river ecology, evidencing that the whole range of (intra-annual and inter-annual) variations of streamflows concurs to shape form and functions of riverine systems. The temporal variability of the streamflows observed in natural basins reflects the randomness inherent in the underlying rainfall and climatic forcings, and the heterogeneity of the hydrological processes determining the release of water from hillslopes to the river network up to the control section where streamflow distributions are evaluated. These considerations led to the qualitative concept of natural streamflow regime [e.g., Sparks, 1992; Poff et al., 1997], meant as a measure of the dynamic state of rivers as determined by naturally varying rainfall, climate and hydrologic conditions.

[3] The control exerted by the natural streamflow regime on the related ecological services of river systems is mediated by several physical variables closely dependent on the flow magnitude, like, e.g., water temperature, turbidity, stream velocity and sediment, nutrient and dissolved oxygen loads [Richter et al., 1997; Constantz, 1998; Smith et al., 2003]. For instance, the timing and duration of low-flow pulses can strongly influence stream biodiversity, inducing extinction or migration of biotic communities (due to, e.g., streamflow temperature variations or increased dissolution of toxic compounds [Davies, 1986]) and promoting the colonization of new species. Thus, the maintenance of the natural hydrologic variability is essential in preserving native riverine biota and ecosystem integrity [e.g., Galat and Lipkin, 2000; Ward et al., 2001; Bunn and Arthington, 2002; Mathews and Richter, 2007].

[4] Many engineered catchments throughout the world, however, and in particular most river systems of the Alpine regions, have experienced major streamflow alterations induced by water resources exploitation for human needs, such as agricultural, hydropower, industrial and civil uses. Nearly complete hydropower potential saturation has been experienced in Italy in the last century, for instance. Today hydroelectric power production represents the most widespread water use in mountain basins throughout the world. Dam regulation strategies aimed at optimizing the power production are responsible for producing significant hourly, daily, weekly, monthly and seasonal fluctuations in streamflows, which may potentially threat the integrity of fluvial systems (let aside the problem of habitat fragmentation) leading to notable morphological and ecological impacts. As a result, anthropogenic catchments both the interannual and the intra-annual variability of the natural flows (which
are of primary importance for successful life cycle completion of aquatic species) are significantly perturbed.

[5] Quantifying the alterations produced by anthropogenic regulation in river basins represents a key task for hydrologists and water managers to set policies and restoration strategies aimed at maintaining the morphological and ecological services associated to riverine ecosystems. From a theoretical point of view, such a goal can be achieved by the following two different types of approaches: (1) data-driven approaches, which focus on the differences exhibited by streamflow statistics before and after the construction of the reservoirs [e.g., Richter et al., 1996, 1997] and (2) model-based frameworks, which rely on the comparison between the statistics of the observed streamflows and that characterizing the flows that would be observed in absence of human regulations, suitably reconstructed by means of numerical or analytical models. The first strategy requires the broad availability of streamflow measurements before the construction of the regulation devices, which are in many circumstances rather difficult to find [see, e.g., Richter et al., 1997]. Moreover, the comparison between the streamflows observed before the construction of the dams and those observed in the postimpact period does not allow an objective and clear distinction between the effect induced by climate changes and that produced by anthropogenic regulations in catchments which experienced strong climatic gradients inclusive, say, of a vanishing cryosphere. Model-based approaches, instead, do not necessarily require streamflow measurements in the preimpact period and allow a direct estimate of the effect of the regulation operations alone. Even though model-based approaches are inevitably affected by the uncertainty associated with the model estimation of the natural streamflow regime, in practice they often represents a valuable tool to single out the effects of anthropogenic regulation activities on riverine systems.

[6] Several approaches have been proposed in the literature to describe anthropogenic streamflow modifications at multiple timescales, including empirical methodologies, hydraulic-based approaches and the range of variability framework [see, e.g., Richter et al., 1997]. In this paper we propose a quantitative method to estimate the natural streamflow regime of a river basins in the absence of streamflow measurements prior to the disturbances whose effects need to be quantified. The approach is based on the analytical stochastic model recently developed by Botter et al. [2007a], which allows a characterization of the streamflow probability density function (pdf) by means of a few climate, soil and vegetation parameters. In particular, the approach focuses on the comparison between the features of the seasonal pdf of the observed discharges and of the natural streamflow pdf estimated by the model. The approach has been termed ecohydrologic because the estimate of the natural streamflow variability embeds the randomness of rainfall and the interaction/competition between hydrologic and biologic processes (e.g., transpiration vs recharge and runoff). The changes induced on the pdf of streamflows allow a direct quantification of the effects of anthropogenic management on the average water resources availability and on flow variability.

[7] Although suitable to evaluate any type of anthropogenic disturbance like, for instance, land use changes, the approach developed is applied to evaluate the degree of alteration produced by dam operations in the intra-annual variability of streamflows within a highly regulated alpine catchment in north-eastern Italy, the Piave river. The case study analyzed provides the opportunity to assess the impact of water resources management strategies and availability along a river network also in view of the possible occurrence of ecologically critical states characterized by low flows. Structural limitations of approaches based on minimum streamflow requirements (that are widely used in Italy and throughout the world to guide water policies and management strategies) are also evidenced and analyzed.

2. Water Resources Management in the Piave River

[8] The Piave river is a relatively large catchment located in north-eastern Italy, flowing from the Alps to the Adriatic Sea. The closure of the mountainous part of the catchment (which represents the object of our analyses) is ideally located near Nervesa, TV (45°49′42″N, 12°12′33″E). The overall area of the catchment at its closure in Nervesa is about 3900 km², while the average elevation is about 1300 m a.s.l. (with a maximum elevation of 3364 m a.s.l.). The spatial distribution of soil uses in the Piave catchment has been derived by applying standard classification techniques to multiple band satellite images (LANDSAT5 and LANDSAT7). Notwithstanding the presence of small-scale heterogeneity in restricted areas of the catchment, at large spatial scales (e.g., O(10) km²) the observed soil uses appear to be relatively homogeneous, with a clear pattern associated to elevation emerging at the scale of the whole basin. In the range from 500 to 1800 m a.s.l., the surfaces are predominantly covered by evergreen and deciduous forests (mainly conifers and broad leaved trees), while alpine pasture/prairies and rock emergence dominate at higher elevations (say above 1800 m a.s.l.). Crops can be found only in the lower part of the basin, typically below 500 m a.s.l. Impervious surfaces are limited (<5%) and relatively sparse, and they are mainly localized along the main stream of the Piave River and, reasonably, at the widespread alpine rock emergences. The main stream of the Piave catchment runs from the sources near the Monte Peralba to the closure section of Nervesa, covering a distance of about 150 km.

[9] The major tributaries of the Piave river are the Boite creek, the Ansiei creek, the Cordevole river and the Mis creek. The observed drainage density slightly decreases from North to South, following the decrease of the slope and of the incision of the landscape. A reliable reconstruction of the underlying river network has been achieved from 100 × 100 m² digital terrain map (DTM) by imposing for simplicity a threshold on the drainage area alone [e.g., Tarboton, 1997]. The river network derived from the DTM counts about 1000 reaches, and is shown in Figure 1a for illustrative purposes. Indeed, the shape of the underlying river network is immaterial for the computation of the natural streamflow regime, as the model (which is designated for daily timescales) neglects the dispersion introduced by channel transport processes.

[10] Despite a century long history of conflicting water uses, especially in the last century the Piave river basin has experienced a rapid increase of the anthropogenic exploitation of its water resources which followed from the construction of a series of dams and reservoirs built along its main stream and the most important tributaries from 1930 to
1960. Nowadays 13 major reservoirs (Table 1), mainly devoted to hydropower production, and a number of diversions and other regulating hydraulic devices, contribute to the management of the river flows in the mountain range of the Piave basin. The temporal evolution of the discharge, downstream of major regulation devices, is strongly influenced by the reservoir operations and their underlying management criteria. The complexity of the system is increased by the parallel presence of an artificial hydraulic network carrying significant flows. Such utilization artefact is superimposed to the natural river network to serve as a linkage among the various reservoirs and energy production sites (Figure 1b). Figure 1b also evidences that a non-negligible part of the discharges originating from the Piave catchment is diverted from the watershed to the outer Livenza basin (at the maximum rate of 40 m$^3$/s) by a pumping system located in correspondence to the S. Croce lake. During the growing season, a nonnegligible fraction of the streamflows (on average about 80 m$^3$/s) is also diverted for irrigation uses from the main stream by a series of intake works and collecting channels located in the low part of the catchment (Figure 1b). The impact of civil and industrial uses, instead, is negligible if compared to that produced by agricultural and hydropower management.

[11] Rather strong modifications have been observed in the energy production strategies since the 1960s by changes of the social and economic pressures (e.g., industrial development, massive increase of tourism during summer and winter, major increases in energy demands) and by the liberalization of the energy market occurred (in Italy and throughout Europe) starting from the beginning of this century. Whereas until a few decades ago the regulation operated by reservoirs serving hydropower plants had been predominantly seasonal (e.g., the reservoirs stored water in summer, released it during winter), more recently important subdaily, daily, weekly, monthly and seasonal fluctuations in the underlying regulation operations have appeared, making the picture far more complex. Moreover, the liberalization of the energy market have introduced strongly unpredictable components into the system behavior related to the energy price.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Coordinates</th>
<th>Drainage Area (km$^2$)</th>
<th>Storage Volume (Mm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santa Caterina</td>
<td>46°32′20″N 12°27′46″E</td>
<td>255</td>
<td>5.5</td>
</tr>
<tr>
<td>Comelico</td>
<td>46°31′58″N 12°30′02″E</td>
<td>355</td>
<td>1.4</td>
</tr>
<tr>
<td>Vodo di Cadore</td>
<td>46°25′04″N 12°14′28″E</td>
<td>326</td>
<td>0.7</td>
</tr>
<tr>
<td>Valle di Cadore</td>
<td>46°24′41″N 12°19′12″E</td>
<td>380</td>
<td>2.9</td>
</tr>
<tr>
<td>Pieve di Cadore</td>
<td>46°23′20″N 12°23′15″E</td>
<td>818</td>
<td>47.9</td>
</tr>
<tr>
<td>Pontesi</td>
<td>46°20′00″N 12°13′38″E</td>
<td>151</td>
<td>0.8</td>
</tr>
<tr>
<td>Val Gallina</td>
<td>46°13′05″N 12°19′59″E</td>
<td>14</td>
<td>5.9</td>
</tr>
<tr>
<td>Ponte Ghirlo</td>
<td>46°20′38″N 11°58′24″E</td>
<td>419</td>
<td>0.1</td>
</tr>
<tr>
<td>Mis</td>
<td>46°09′39″N 12°04′57″E</td>
<td>108</td>
<td>36.0</td>
</tr>
<tr>
<td>La Stua</td>
<td>46°07′47″N 11°56′51″E</td>
<td>28</td>
<td>3.5</td>
</tr>
<tr>
<td>Fedaia</td>
<td>46°27′38″N 11°51′17″E</td>
<td>8</td>
<td>17.0</td>
</tr>
<tr>
<td>Cavia</td>
<td>46°21′36″N 11°49′07″E</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>Alleghe</td>
<td>46°23′52″N 12°00′46″E</td>
<td>245</td>
<td>2.7</td>
</tr>
<tr>
<td>Santa Croce</td>
<td>46°07′24″N 12°19′15″E</td>
<td>136</td>
<td>86.7</td>
</tr>
</tbody>
</table>
The alterations of the streamflow regime observed in the Piave river downstream of the reservoir and diversion systems inevitably reflect the whole sequence of regulations operated by the water managers at multiple timescales, which in turn depends on the (random) fluctuations occurring in the electricity market and in water availability. The dynamic behavior of the water exploitation system in the Piave river basin proves thus a significant test for an objective quantification of dam-induced alterations of the natural streamflow regime.

3. Methods

In a series of recent papers, Botter et al. [2007a, 2007b, 2007c, 2008] have provided an analytical characterization of the probability density function (pdf) of streamflows on the basis of a stochastic description of the dynamics involving the average soil moisture content of a representative hydrologically active soil layer. This section summarizes the main features of the model, which represents the key analytical tool for our investigation.

The approach is based on the long-term soil water balance in the root zone, where the competition between deep percolation and evapotranspiration processes takes place. The relevant processes occurring therein are modeled at daily timescales through a simplified approach which uses spatially averaged parameters to describe the geometrical configuration of the relevant control volume: the root zone depth (i.e., the depth of the active soil layer), \( Z_r \) [L] and its porosity, \( n \) (dimensionless) [Porporato et al., 2004; Settin et al., 2007; Botter et al., 2007a, 2007c]. The temporal evolution of spatially averaged relative soil moisture in the root zone, \( s(t) \), is thus seen as the result of the following three processes [see Rodriguez-Hurbe and Porporato, 2004]:

1. Stochastic instantaneous increments due to infiltration from rainfall (which is modeled, at daily timescales, as a zero-dimensional marked Poisson process). In particular, the average frequency of rainfall events is \( \lambda_p \) \([ T^{-1}]\), while daily rainfall depths are assumed to be exponentially distributed with parameter \( \gamma_p \) \([ L^{-1}]\).

2. Losses due to evapotranspiration, which are assumed to increase linearly from 0 (at the wilting point, \( s_w \), up to the potential value \( ET \) \([ L/T] \) (at a suitable soil moisture threshold comprised between field capacity and saturation, \( s_f \)). The parameters \( ET \), \( s_w \), and \( s_f \) are assumed to be representative for the evapotranspiration process occurring in the considered basin during a given season and for a given state of the ecosystem.

3. Instantaneous deep percolation producing effective rainfall and hence runoff (above the threshold \( s_1 \)).

The approach has been originally developed to deal with the soil water balance in relatively small basins where spatially uniform rainfall, soil and vegetation properties can be assumed. Later results by Botter et al. [2007c], however, have suggested that the same model can be effectively used to predict the probability density functions of streamflows also in relatively large catchments (i.e., \( A \sim O(10^3) \) km\(^2\)) provided that mean residence times in unchanneled states remain relatively large with respect to what spent within the channels.

According to the above scheme, when \( s \) exceeds the threshold \( s_1 \) due to an infiltration input, it is assumed that the soil moisture content instantaneously decreases to \( s_1 \) through the release of an effective rainfall pulse, which propagates through the outlet as subsurface runoff [Porporato et al., 2004]. Effective rainfall time series resulting from the soil moisture dynamics described above may be approximated, at the daily timescale, by a new marked Poisson process [Botter et al., 2007a] where the net rainfall depths (i.e., the fraction of the incoming rainfall pulses determining the exceedance of the threshold \( s_1 \)) follow an exponential distribution still with parameter \( \gamma_p \). The related average frequency of effective rainfall (i.e., runoff) events, \( \lambda \), may be obtained so as to average crossing rates of the threshold \( s_1 \), and is expressed in terms of the underlying soil, vegetation and rainfall properties as [Botter et al., 2007c]

\[
\lambda = \eta \frac{\exp(-\gamma_p)}{1 - \exp(-\gamma_p) \gamma_p^\lambda},
\]

where \( \Gamma(\alpha, b) \) is the lower incomplete gamma function of parameters \( a \) and \( b \) (see, e.g., Botter et al. [2007a] for mathematical details), \( \eta = ET(nZ(s_1 - s_w)) \) is the normalized maximum evapotranspiration rate and \( \gamma_p = \gamma_p(nZ(s_1 - s_w)) \) is the ratio between the soil storage capacity and the mean rainfall depth.

The effective rainfall pulses infiltrating beyond the root zone are assumed to propagate through deeper soil layers as subsurface and/or groundwater flow and eventually be released to the channel network as subsurface/groundwater flow. As long as the response time of subsurface states is thought of as an exponentially distributed random variable [Botter et al., 2007a, 2007b, 2007c, 2008] the temporal evolution of subsurface/groundwater contribution to streamflows, \( Q \), is made up of instantaneous jumps (in correspondence of each effective rainfall event) and exponential decays (in between the events). Accordingly, the steady state pdf of \( Q \), \( p(Q) = p(Q, t \to \infty) \), can be expressed by a Gamma distribution [Botter et al., 2007a, 2007c]

\[
p(Q) = c^{-Q^{\gamma_p}} \exp(-\gamma_p Q),
\]

where \( k \) \([ T^{-1}] \) is the inverse of the mean response time in subsurface groundwater. \( \gamma_p = \gamma_p(k A) \) represents the mean runoff increment due to incoming rainfall events and

\[
c = \frac{\gamma_p^\gamma_p}{\Gamma(\gamma_p)}
\]

Note that the above model neglects the fact that fast surface runoff components triggered by intense storms are usually characterized by relatively short characteristic timescales. In many cases of interest, however, (and certainly for low flows) the overall subsurface/groundwater contributions to streamflows largely exceed possible fast responses of a catchment, particularly at the daily timescale and in absence of extensive impermeable surfaces [Botter et al., 2007c]. Nevertheless, the above approximation may lead to underestimated probabilities for the largest streamflows, which will be thus disregarded in our analyses. Moreover, regional recharge from deep aquifers and interferences due to snow melting/accumulations are not included in the model. A detailed discussion on the major merits of the approach, and on the limits of applicability (which do not provide any concern for the case study handled in the paper) are given by Botter et al. [2008].

The proposed approach is based on the prediction of the streamflow statistics that would have been observed in
absence of anthropogenic alterations. The method consists of the following steps:

1. Application of the model to unregulated sections (section 4.1). The preliminary application of the model to smaller, unregulated catchments of the Piave basin allows a proper verification of the model’s capability to reproduce the natural streamflow regime along the Piave river, and of the robustness of the procedure used to derive the model parameters from hydrologic information. The information gathered for the unregulated catchments is central to identify the model parameters operating also at the larger scales (see step 2).

2. Estimate of the model parameters at the scale of subcatchments which includes regulation devices (section 4.2). The scale of interest are in this case larger than that handled during the first step, and the lack of streamflow time series which refers to natural (i.e., unregulated) conditions may render the parameter identification procedure more troublesome.

3. Application of the model to catchments affected by anthropogenic regulation, and comparison between the model prediction of the natural streamflow regime and the observed streamflow statistics (section 4.3). The measurements available in the preimpact period will be used to assess the robustness of the approach.

4. Key features of the 18 (regulated and unregulated) subcatchments of the Piave basin considered in this study are reported in Table 2. The geomorphic and vegetation features of each subcatchment have been obtained via suitable GIS-based manipulation of the DTM and of soil type/cover maps.

4. Results

4.1. Probabilistic Streamflow Characterization in Unregulated Sections

To test the ability of the model to reproduce the statistics of the observed discharges in the Piave river and verify the robustness of the procedure for the parameter identification, the analytical streamflow pdf given by equation (2) has been compared to the empirical pdfs from measurements at the closure of eight carefully chosen pristine (i.e., unaffected by significant regulation) subcatchments of the Piave basin (with an area ranging from 8 to 350 km²). For brevity, we shall report here only the results of the comparison between modeled and observed streamflow statistics in the following basins: the Boite creek at Cancia, the Cordevole river at Saviner, and the Fiorentina creek at Sottorovei (Figure 2). None of the conclusions presented here is significantly different from those obtained for all other basins examined.

The catchment of the Boite creek at Cancia is an alpine watershed of 315 km² located in the north-eastern part of the Piave basin. Soils are mainly covered by forests, grazing and highly fractured rocks near the top of the mountains (inset of Figure 2a). Daily streamflows have been measured at the outlet of Cancia (46°25′54″N, 12°13′16″E) from 1986 to 2008, while the rainfall measurements exploited to derive the statistics of the spatially averaged rainfall rates in this catchment are that recorded at Podes-

<table>
<thead>
<tr>
<th>Study</th>
<th>Catchment</th>
<th>Area (km²)</th>
<th>Years</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Padola at S.Stefano</td>
<td>130</td>
<td>1986–2007</td>
<td>Natural</td>
</tr>
<tr>
<td>2</td>
<td>Piave at Ponte della Lasta</td>
<td>355</td>
<td>1989–2006</td>
<td>Natural</td>
</tr>
<tr>
<td>3</td>
<td>Piave at Comelico reservoir</td>
<td>355</td>
<td>1990–2002</td>
<td>Regulated</td>
</tr>
<tr>
<td>4</td>
<td>Piave at Pelos</td>
<td>614</td>
<td>1990–2002</td>
<td>Regulated</td>
</tr>
<tr>
<td>5</td>
<td>Piave at Perarolo</td>
<td>828</td>
<td>2004–2008</td>
<td>Regulated</td>
</tr>
<tr>
<td>6</td>
<td>Boite at Podestagno</td>
<td>82</td>
<td>1992–2008</td>
<td>Natural</td>
</tr>
<tr>
<td>7</td>
<td>Boite at Cancia</td>
<td>313</td>
<td>1986–2008</td>
<td>Natural</td>
</tr>
<tr>
<td>8</td>
<td>Boite at Vodo</td>
<td>326</td>
<td>1990–2002</td>
<td>Regulated</td>
</tr>
<tr>
<td>9</td>
<td>Piave at Soverzene</td>
<td>1687</td>
<td>2001–2008</td>
<td>Regulated</td>
</tr>
<tr>
<td>10</td>
<td>Piave at Ponte nelle Alpi</td>
<td>1929</td>
<td>2001–2008</td>
<td>Regulated</td>
</tr>
<tr>
<td>12</td>
<td>Cordevole at La Vizza</td>
<td>8</td>
<td>1984–2008</td>
<td>Natural</td>
</tr>
<tr>
<td>13</td>
<td>Cordevole at Saviner</td>
<td>109</td>
<td>1990–2008</td>
<td>Natural</td>
</tr>
<tr>
<td>14</td>
<td>Fiorentina at Sottorovei</td>
<td>58</td>
<td>1993–2008</td>
<td>Natural</td>
</tr>
<tr>
<td>15</td>
<td>Cordevole at Ponte Mas</td>
<td>711</td>
<td>2003–2008</td>
<td>Regulated</td>
</tr>
<tr>
<td>16</td>
<td>Cordevole at Sass Muss</td>
<td>715</td>
<td>1991–2004</td>
<td>Regulated</td>
</tr>
<tr>
<td>17</td>
<td>Sonna at Feltre</td>
<td>120</td>
<td>1985–2007</td>
<td>Natural</td>
</tr>
<tr>
<td>18</td>
<td>Piave at Segusino</td>
<td>3537</td>
<td>2004–2008</td>
<td>Regulated</td>
</tr>
</tbody>
</table>

Figure 2. Observed and analytical streamflow probability density functions in three unregulated sections: (a) Boite at Cancia, (b) Cordevole at Saviner, and (c) Fiorentina at Sottorovei.
tagno, Faloria and Borca di Cadore from 1986 to 2008, and the rainfall data recorded at Cortina d’Ampezzo from 1992 to 2008. The full set of rainfall, soil, vegetation and morphologic parameters for the Boite creek catchment is reported in Table 3. Note that the observed streamflows do not decrease below the threshold 0.03 cm/d in the whole observation period, most likely due to snow melting and/or karst phenomena (typical in some areas of the basin) which determine the slow release of spring precipitation during the summer. Hence, the comparison between modeled and observed streamflow pdf’s has been carried out after translating by a value of 0.03 cm/d the analytical streamflow pdf. Details on parameter estimation follow.

[30] Due to the observed intra-annual variability of the hydrologic regime of the Piave basin, and in order to avoid interferences produced by snow melting which are not considered here, the comparison between theoretical and observed daily streamflow pdfs is carried out only during the summer season (June to August). Note that in all the cases explored the three model parameters (λ, k and γ) have been derived from relatively simple hydrologic and morphologic information as follows. The parameter k (i.e., the inverse of the mean rainfall depth during wet days and the exponential distribution assumed by the model.

[31] On this basis, the parameter γ can be calculated from the values of the parameters γp, k and A (which represents the area of the considered subcatchment), according to the definition given in section 2. Finally, the runoff frequency λ can be calculated using equation (1). The value of the remaining soil and vegetation parameters (s1 − sw, ET, n Z) are obtained by calibration. In this study, the difference between s1 and sw has been assumed to be 0.8 [Rodriguez-Iturbe and Porporato, 2004], while the effective soil depth (n Z) has been determined by exploiting soil type and geopedologic information. The values obtained, which have been assumed to be constant among the various subcatchments considered, have been also compared with the values derived from the calibration of a geomorphologic rainfall-runoff model of the hydrologic response applied to the same catchments, showing an overall agreement between the two independent estimates of these parameters [Rinaldo et al., 2005]. Finally, the maximum evapotranspiration ET have been calculated on the basis of land cover and climatic data as by Botter et al. [2007b], adjusted to the best fit between observed and modeled streamflow distributions.

[32] The theoretical gamma distribution, which is representative in this case of a wet streamflow regime where no ephemeral flows exist, is found to reproduce remarkably well the observed streamflow pdf (Figure 2a). In particular, both the mode and the peak of the distribution are closely represented by the analytical model. The relative error in the

derived by comparing the observed distribution of spatially averaged daily depths during wet days and the exponential distribution assumed by the model.

Table 3. Parameters of the Analytical Model for All the Piave Subcatchments Considered in This Study

<table>
<thead>
<tr>
<th>Study</th>
<th>Catchment</th>
<th>λ (d⁻¹)</th>
<th>ETmax (cm/d)</th>
<th>s1−sw (cm)</th>
<th>nZ (cm)</th>
<th>λd (d⁻¹)</th>
<th>γp (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Boite at Cancia</td>
<td>0.065</td>
<td>0.2</td>
<td>0.8</td>
<td>15</td>
<td>0.65</td>
<td>1.53</td>
</tr>
<tr>
<td>9</td>
<td>Piave at Soverzene</td>
<td>0.05−0.07</td>
<td>0.25</td>
<td>0.8</td>
<td>15</td>
<td>0.69</td>
<td>1.46</td>
</tr>
<tr>
<td>13</td>
<td>Cordevole at Saviner</td>
<td>0.08</td>
<td>0.3</td>
<td>0.8</td>
<td>15</td>
<td>0.63</td>
<td>1.39</td>
</tr>
<tr>
<td>14</td>
<td>Fiorentina at Sottorovei</td>
<td>0.10</td>
<td>0.25</td>
<td>0.8</td>
<td>15</td>
<td>0.57</td>
<td>1.23</td>
</tr>
<tr>
<td>16</td>
<td>Cordevole at Sass Muss</td>
<td>0.06−0.09</td>
<td>0.3</td>
<td>0.8</td>
<td>15</td>
<td>0.68</td>
<td>1.58</td>
</tr>
<tr>
<td>18</td>
<td>Piave at Segusino</td>
<td>0.04−0.07</td>
<td>0.27</td>
<td>0.8</td>
<td>15</td>
<td>0.72</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Table 4. Statistics of the Observed and Analytical Streamflow pdfs in Some Regulated and Unregulated Cross Sections of the Piave Basin

<table>
<thead>
<tr>
<th>Study</th>
<th>Catchment</th>
<th>Qmean</th>
<th>Qmedian</th>
<th>CVobs</th>
<th>CVET</th>
<th>CVETa</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Boite at Cancia</td>
<td>1.13</td>
<td>1.10</td>
<td>1.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Cordevole at Saviner</td>
<td>1.17</td>
<td>1.07</td>
<td>1.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Fiorentina at Sottorovei</td>
<td>1.07</td>
<td>1.45</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Piave at Soverzene</td>
<td>0.21</td>
<td>2.24</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Cordevole at Sass Muss</td>
<td>0.41</td>
<td>2.95</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Piave at Segusino</td>
<td>0.23</td>
<td>2.47</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Here (Q) is the mean, CV is the coefficient of variation, and m is the mode. We report here the ratio between observed and analytical values. In regulated sections the statistics representative of natural conditions have been calculated using the upper limit of the range singled out for the mean residence time. In natural sections, values of the ratio between observed and theoretical statistics close to unit thus indicate good model performances, while in regulated sections the departure from the unit measures the degree of alteration."
model estimate of the mean ($\langle Q \rangle$), of the mode ($m$) and of the coefficient of variation ($CV$) of the observed pdf does not exceed 15% (Table 4). Figure 2b shows the results of the comparison between modeled and observed streamflow statistics for the catchment of the Cordevole river at Saviner, a mountain catchment of 110 km$^2$ in the north-western part of the basin. The catchment outlet is located upstream of the confluence between the Cordevole and the Pettorina creek. Soils are mainly covered by forests. Daily streamflows have been continuously measured at the outlet of Saviner (46°26′S, 11°59′18″E) from 1990 to 2008. Rainfall data, instead, have been taken from the measurements available at the stations of Passo Pordoi, Arabba and Passo Falzarego in the same time period. The values taken by the model parameters are shown in Table 3. Similarly to Figure 2a, the analytical pdf has been shifted by 0.02 cm/d to account for the presence of a constant base flow component originating from long-term fractured rock releases. The agreement between observed and predicted streamflow pdf is satisfactory, even though the analytical model slightly underestimates the first moment of the observed streamflow distribution (see Table 4).

The result of the comparison between modeled and observed streamflow statistics for the Fiorentina creek catchment at Sottorovei are shown in Figure 2c. The Fiorentina creek is a small tributary of the Cordevole river, which has an area, at the closure of Sottorovei, of about 60 km$^2$. Soils are mainly covered by forest, with the presence of fractured rock emergences and gravel fans at high elevations. Daily streamflows have been measured at the outlet of Sottorovei (46°26′20″N, 12°00′29″E) from 1993 to 2008. In the same period, daily rainfall measurements are available at the nearby stations of Passo Falzarego and Caprile. Rainfall measurements are also available at Pescul from 2002 to 2008. The numerical values assumed by all the model parameters for the Fiorentina creek catchment are reported in Table 3. The general agreement between observed and predicted statistics is satisfactory (Table 4), even though in this case the model slightly underestimate the peak of the probability distribution. The observed mean appears to be very close to the mean streamflow predicted by the analytical model, while the coefficient of variation of the observed pdf is somewhat larger than the corresponding analytical values.

Overall, the comparisons performed evidence the robustness of the analytical scheme (and of the parameters’ estimation procedure) to reproduce the major features of the observed streamflows (shape and mode of the pdf, first-order moments) in different unregulated subcatchment of the Piave basin, suggesting the potential applicability of the model to evaluate the natural streamflow regime in downstream regulated sections.

### 4.2. Estimate of the Model Parameters in Regulated Catchments

[35] The application of the analytical model to catchments where the sequencing of streamflows depends on regulation operations requires a procedure to identify the model parameters at the scales of interest. In particular, at these scales the estimate of the parameter $k$ (which represents the inverse of the mean response time of subsurface states), in absence of streamflow measurements unaffected by the anthropogenic regulation, may require particular care, as discussed below.

[36] In regulated catchments, the rainfall parameters are derived using the same procedure employed at smaller scale and described in section 4.1, the only difference being that, in larger catchments, the number of meteorological stations used to derived spatially averaged rainfall rates increases. For each catchment, indeed, we have used data from all the available meteorologic station located within the considered basin. Nevertheless, the Poissonian nature of the rainfall process and the probability distribution of the averaged rainfall depths can be properly checked after a suitable spatial average of the available measurements.

[37] Importantly, the parameters $n$, $Z_0$, and $(s_1-s_m)$ have been kept constants among the various catchments, an assumption supported also by results from numerical simulations of a geomorphic-based model of the hydrologic response in the Piave catchment [Rinaldo et al., 2005]. The potential evapotranspiration rate ($ET$) has been estimated assuming the ratio between $ET$ and the relative fraction of vegetated areas within the various catchments, $\phi_v$, to be constant throughout all the subcatchments considered. Indeed, the ratio between the values of $ET$ estimated from climatic data and the values of $\phi_v$ observed remains approximately constant in all the catchments identified by the 8 unregulated cross sections where the comparison between theoretical and observed streamflow pdf has been carried out (Table 5). The proportionality constant between $ET$ and $\phi_v$ has been thus derived as the average ratio between the calibrated values of $ET$ in such catchments and the corresponding values of $\phi_v$ observed therein.

[38] The determination of the mean response time in subsurface ($\langle \tau \rangle = 1/k$) (which under natural conditions rely on hydrometric observations) becomes particularly troublesome for catchments affected by anthropogenic regulations when streamflow measurements under natural flow conditions are not available. For the above reason, the mean response time in regulated catchments has been estimated by a regression method which exploits the information available at smaller scales [see, e.g., Rinaldo et al., 2005]. In particular, in order to account for the uncertainty existing in the specification of the mean response time at larger scales, the approach defines a range of possible values of $\langle \tau \rangle$, within which the actual response time may most likely be found. In particular, the range of values for the mean response time that would be observed under unregulated conditions in a regulated catchment with area $A$, $\langle \tau \rangle_r$, is calculated as

$$\langle \tau \rangle_r = \frac{\sum_i A_i \langle \tau \rangle_i + (A - \sum_i A_i) \langle \tau \rangle_s}{A},$$

(3)

where $\langle \tau \rangle_i (i = 1, N)$ are the mean response times estimated from hydrometric observations at the closure of the largest

---

**Table 5.** Correlation Among Evapotranspiration Rates and Vegetated Fraction in Various Subcatchment of the Piave River

<table>
<thead>
<tr>
<th>Catchment</th>
<th>$ET$ (cm/d)</th>
<th>$\phi_v$</th>
<th>$\frac{ET}{\phi_v}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boite at Podestago</td>
<td>0.2</td>
<td>0.57</td>
<td>0.35</td>
</tr>
<tr>
<td>Boite at Cancia</td>
<td>0.2</td>
<td>0.77</td>
<td>0.26</td>
</tr>
<tr>
<td>Cordevole at La Vizza</td>
<td>0.25</td>
<td>0.92</td>
<td>0.27</td>
</tr>
<tr>
<td>Cordevole at Saviner</td>
<td>0.3</td>
<td>0.97</td>
<td>0.31</td>
</tr>
<tr>
<td>Fiorentina at Sottorovei</td>
<td>0.3</td>
<td>0.92</td>
<td>0.33</td>
</tr>
<tr>
<td>Padola at S. Stefano</td>
<td>0.3</td>
<td>0.91</td>
<td>0.33</td>
</tr>
<tr>
<td>Piave at Ponte della Lasta</td>
<td>0.3</td>
<td>0.89</td>
<td>0.34</td>
</tr>
</tbody>
</table>
for the portion of the basin (whose area equals 1991 square kilometers) between the pdf of observed streamflow in the period 1991–2004 (dots) and the natural streamflow pdf predicted by the model (solid curve). Note that, in principle, the application of the model at large spatial scales could be problematic, because of the point-wise nature of the description of the underlying rainfall and soil moisture dynamics (and the simplified morphology implicitly assumed by the model). Botter et al. [2007c] and Settin et al. [2007], however, have shown the potential of the approach to describe the statistics of spatially averaged soil moisture dynamics via effective parameters also in relatively large, heterogeneous catchments.

4.3. Assessing Streamflow Alterations Induced by Reservoir Operations

The analytical model described in section 2 has been applied to 10 regulated catchments of the Piave basin with area ranging from 320 to 3500 km². These include several important dams and diversions affecting the pdf of the observed streamflows. The impact of the regulations devices on the hydrologic regime is assessed by comparing the theoretical distribution of the natural flows predicted by the model and the observed streamflow pdf. Note that the temporal resolution of the model (daily) and its reference time horizon (a single season) allow a proper evaluation of the streamflow alterations occurring from daily to monthly timescales. For brevity we shall focus here only on the results obtained from the application of the model to the Cordevole river at Sass Muss, the Piave River at Soverzene and the Piave river at Segusino. The other results point at the same conclusions.

The Cordevole river is one of the most important right tributaries of the Piave River. At the closure section of Sass Muss, which is located a few kilometers upstream of the confluence with the Piave river, the Cordevole catchment has an area of about 710 km². Soils are mainly covered by forests and grazing pastures, while highly fractured rock emergences prevail at the highest elevations (Figure 3a). The catchment includes 3 reservoirs (with an overall regulation volume of 5.1 · 10⁶ m³) and a few hydropower plants. The artificial network serving these reservoirs is relatively complex, and its structure is sketched in Figure 3b. Daily streamflows have been measured at Sass Muss (46°08′23″N, 12°07′01″E) from 1991 to 2004, while the corresponding rainfall measurements used to derive the statistics of the spatially averaged rainfall rates are that recorded at Arabba, Caprile, Malga Ciapela, Passo Falzarego, Passo Pordoi, Passo Valles, Cencenighe and Gares (from 1991 to 2004), and that recorded in other stations active during shorter time periods. The underlying rainfall, soil, vegetation and morphologic parameters of the analytical model for the Corde-

$N$ not overlapping unregulated subcatchments contained within the considered catchment, and $A_i$ the corresponding area. $\langle \tau \rangle_k$ is the unknown value of the mean response time for the portion of the basin (whose area equals $A - \sum A_i$) for which there is no information available. For the sake of simplicity, the latter is assumed to be comprised in the following range:

$$\langle \tau \rangle_k \in \left[ \frac{\langle \tau \rangle_{\text{aver}}}{1 + \xi} \langle \tau \rangle_{\text{max}} \right].$$

where $\langle \tau \rangle_{\text{aver}} = \left( \sum A_i \langle \tau \rangle_i \right) / \sum A_i$ is the average of the mean response times evaluated at the closure of the largest $N$ not overlapping unregulated subcatchments contained in the considered catchment where the model has been applied. Moreover, $\langle \tau \rangle_{\text{max}} = \max \{ \langle \tau \rangle_i \}$ is the maximum of the above mean response times, and $\xi$ is an empirical parameter accounting for the fact that the mean response time can increase with the area of the catchment due to the decrease of the drainage density and of the topographic slopes. The value chosen for $\xi (0.5)$ has been obtained via calibration by comparing equations (3) and (4) with the values obtained for the mean response time from streamflow data in a number of nested unregulated catchments where streamflow measurements are available.

Figure 3. Effect of the anthropogenic regulations in the Cordevole river at Sass Muss: (a) catchment geometry; (b) artificial network for hydropower production; (c) comparison between the pdf of observed streamflow in the period 1991–2004 (dots) and the natural streamflow pdf predicted by the model (solid curves, the two curves refer to the different mean response times for subsurface flow indicated in the legend); (d) MEF–induced change in the observed streamflow pdf after 2001 (observed pdf in the pre-MEF period (dots), and natural streamflow pdf predicted by the model (solid curve)).
Table 3.

In section 4.2, and the corresponding values are reported in vole catchment at Sass Muss have been derived are described (legend).

The model (solid curves, the two curves refer to the different cial network for hydropower production; and (c) comparison Piave river at Soverzene: (a) catchment geometry; (b) artifi-
cultural regulations in the upstream reservoirs. In par-

Cordevole river and diverted toward other reservoirs (thus

and, overall, to the fact that part of the water is kept from the reservoir to be released during other periods of the year)

component in the regulation strategies (a nonnegligible fraction of the summer precipitation is stored within the reservoirs during the early recessions of the hydrograph, which is frequently observed after 2001. The third peak of the observed pdf, around 0.2 cm/d, originates from management operations in the period from April to September 1998, during which the depleting of the Ponte Ghirlo and Alleghe reservoirs was obtained by prolonged releases of high flows from the reservoirs.

[43] The difference between the mean, the coefficient of variation and the mode of the observed pdf and those characterizing the streamflow pdf that would have been observed in absence of anthropogenic regulations are reported in Table 4. Table 4 and Figure 3c evidence that there is a remarkable reduction of the mean, and a pronounced increase of the skewness of the distribution, suggesting that the anthropogenic regulation increases the bias of the distribution, reducing its symmetry. Moreover, the coefficient of variation of the observed pdf is larger that than estimated by the model for unregulated conditions. This means that the anthropogenic regulation produces the increase of the frequency of hydrologic conditions which are relatively far from the mean. In other words, when anthropogenic dis-
turbances become important, the mean of the streamflow pdf loses significance, and it becomes much less representative of the actual hydrologic conditions observed in the field than under natural flow conditions.

[44] In Figure 3d we analyze how the prescriptions introduced in 2001 on the minimum environmental flow (MEF) have impacted the probabilistic structure of the observed streamflows. In particular, the prescription adopted have established that a minimum flow of about 0.03 cm/d should have been guarantied to the Cordevole river at Sass Muss. The plot compares the theoretical natural streamflow pdf predicted by the model with \( \langle \tau \rangle = 17 \) d (solid line) and the pdf of the streamflows observed in the pre-MEF period (1991–2000, diamonds) and in the post-MEF period (2001–2004, circles). The plot, which also reports the value of the MEF as a dash-dotted line, evidences how the pdf of the observed streamflow has significantly changed after the introduction of the prescriptions concerning the MEF. In particular, the mean of the pdf has significantly increased after 2001. Moreover, the mode has increased above the MEF threshold, and the peak appears to be less pronounced with respect to the pre-MEF period. Nevertheless, the modifications of the natural streamflow regime are substantial.

[45] The second example discussed in this section concerns the analysis of the streamflows observed in the Piave river at Soverzene, which hosts an important power plant located in correspondence of a weir. At the closure section of Soverzene, which is located a few kilometers upstream of the small center of Ponte nelle Alpi, the Piave catchment has a drainage area of about 1700 km². Soils are mainly covered by forests, with nonnegligible presence of alpine pastures/prairies soils and pervasive rock emergence at the highest elevations (Figure 4a). The catchment includes 7 reservoirs (with an overall regulation volume of 6.5 \cdot 10^7 m³) and several hydropower plants. The artificial network serving these reservoirs is sketched in Figure 4b to highlight the role of the connections among the various reservoirs and between the natural and the artificial network.

[46] Daily streamflows have been measured at Soverzene (46°11′55″N, 12°17′57″E) from 2001 to 2008, while the corresponding rainfall measurements used to derive the statistics of the spatially averaged rainfall rates are that recorded in 20 meteorological stations within the catchment during the
same time period. The underlying rainfall, soil, vegetation and morphologic parameters of the analytical model for the Piave catchment at Soverzene have been derived as described in section 4.2, and the corresponding values are reported in Table 3. Figure 4c shows the comparison between the observed streamflow pdf (dots) and the natural streamflow pdf predicted by the analytical model described in section 2 (continuous lines) during the period 2001–2008. The two lines in this graph correspond to the extremes of the range of values available for the mean subsurface response time $\tau$ $(\tau = 15$ d, grey line; $\tau = 20$ d, dark line).

[47] The graph evidences that the uncertainty related to the choice of the value of the parameter $k$ is small compared to the effects of the anthropogenic regulation on the natural streamflow regime. The observed pdf has sizably smaller mode and mean and a larger modal probability density than the estimated natural streamflow pdf (see also Table 4). Moreover, the observed pdf shows two additional secondary peaks in correspondence of values of $Q$ larger than the mode. The comparison between some key descriptors of the observed pdf and the corresponding descriptor of the theoretical distribution under natural streamflow conditions is shown in Table 4. Table 4 evidences that the observed pdf has a sensibly smaller mean and mode, and a larger $CV$ than the natural flow pdf estimated by the model. The observed reduction of the mean and of the mode of the pdf is due to a seasonal component in the regulation strategies and to the fact that part of the water flows are diverted to the Livenza catchment, while the increasing in the coefficient of variation is due to the increase of the frequency of extreme states far removed from the mean and characterized by relatively low and high flows.

[48] Note that the mode of the observed distribution practically coincides with the MEF established by the water authority in 2001. Both the secondary relative maxima of the observed pdf, instead, are produced by the management strategies in the upstream reservoirs. In particular, both the relative maxima of the pdf are generated by a prolonged release of the water accumulated in the upstream reservoirs (in particular the Centro Cadore Reservoir, which is the biggest reservoir within the whole catchment) during time periods characterized by a relatively high energy price. This is clearly shown by Figure 5, which reports the temporal evolution of the energy price (Figure 5a) and of the hydrometric level in the Centro Cadore reservoir, altogether with the streamflow observed at Soverzene (Figure 5b), during a sample time window of three months. Starting from the end of Jun 2006, the energy price starts increasing and continues increasing until the end of July 2006. Correspondingly, the hydrometric level in the Centro Cadore reservoir decreases, determining a sudden increase of the flow observed at Soverzene.

[50] To evaluate the streamflow regime currently observed at the cross section of Segusino, we took the daily streamflows measured therein from 2004 to 2008. The corresponding rainfall measurements used to derive the statistics of the spatially averaged rainfall rates are those recorded in 37 meteorological stations within the catchment. The catchment has an area of about 3500 km$^2$ and encompasses most of the mountain part of the Piave basin and includes its main anthropogenic devices (all the reservoirs and most of the derivations, see Figure 6b). This section has been selected because it provides a measure of the alterations induced by the regulation operations on the streamflow regime in the lower part of the Piave river and because of the fact that in this cross section the streamflow measurements available span 8 decades, including a time period before the construction of the major reservoirs of the watershed.

Figure 5. Linkage between the electricity market prices and the streamflow pdf: the increase of the electricity price produces (a) an increase of the power production at Soverzene, which is obtained by depleting the Centro Cadore reservoir (b) with a corresponding increase of the flows at Soverzene in that period.
lected in that period were insufficient to provide reliable information on spatially averaged rainfall rates.

The graph also evidences that the observed pdf has sizably smaller mode and mean and a larger modal probability density than the estimated natural streamflow pdf (see also Table 4). The mode of the observed distribution, in particular, is found near $Q = 0.05$ cm/d, a value four times smaller than the mode of the natural flows. The observed reduction of the water resources at Segusino is mainly due to the various derivations located upstream. The comparison between some key descriptors of the observed pdf and the corresponding descriptor of the theoretical distribution under natural streamflow conditions is shown in Table 4. Again, the observed pdf is found to have a larger coefficient of variation than that characterizing the natural flow pdf.

Our results suggest that the observed pdf downstream of the regulation devices have a smaller mean, a much smaller mode, a larger peak probability and a larger $CV$ than the pdf that would be observed in absence of anthropogenic regulations. In practice, the anthropogenic disturbance lead to a remarkable and quantifiable reduction of the overall water resources available during the summer, with an increase of the frequency of preferential hydrometric states far from the mean.

5. Water Resources Availability and MEF Compliance Percentages Along the Piave River

The streamflow data and the modeling results available in various control sections along the Piave river and its major tributaries, jointly with the information available about the minimum flow requirements prescribed by the Water Authority, allow an estimate of the depletion of water resources induced by hydropower and irrigation uses in the Piave river and a spatially distributed evaluation of the compliance percentages of the MEF in the various reaches of the catchment.

Indeed, by applying the analytical model within the various regulated catchments that include reservoirs and regulation devices allows a robust estimate of the mean streamflow that would be observed during the summer in different control sections along the river network. The difference between the observed and predicted mean streamflow represents a suitable quantification of the effect of the regulation operations on the average availability of water resources in the different control sections considered. Figure 7 shows the spatial distribution of the percentage of reduction of the mean streamflow with respect to unregulated conditions in all the subcatchments of the Piave basin.

Figure 6. Effect of the anthropogenic regulations in the Piave river at Segusino: (a) catchment geometry; (b) artificial network for hydropower production; (c) comparison between the pdf of observed streamflow in the period 2004–2008 (dots) and the natural streamflow pdf predicted by the model (solid curves, the two curves refer to the different mean response times for subsurface flow indicated in the legend). Also shown is the observed streamflow pdf in the period 1928–1940 (diamonds), before the construction of the major reservoirs.

Figure 7. Reduction percentages of the mean summer flow observed in several cross sections of the Piave river basin.
analyzed. The color of the circles codes the deviation from the natural conditions: white circles represent natural sections, while red and orange circles indicates the most critical conditions (with a reduction of the mean streamflow greater than 90% and between 75% and 90%, respectively). The cross sections in which the deviation of the mean streamflow from the natural flow regime is instead less then 50% are indicated by green circles, while yellow circles refer to situations where the decrease of the mean streamflow is between 50% and 75%. Figure 7 indicates that the reduction of the mean streamflow due to anthropogenic regulations is huge in most of the cases examined, the only exception being the section of Pelos, upstream of the Centro Cadore reservoir. The most altered conditions are found along the Piave mainstream in correspondence to the following sections: (1) Piave at the Comelico reservoir, downstream of the Comelico reservoir and upstream of the confluence of the Ansiei creek; (2) Perarolo, downstream of the Centro Cadore reservoir; Soverzene, downstream of the power plant and the weir located herein; and (3) Segusino, in the lower part of the Basin.

Finally, the compliance of the minimum environmental flow (MEF) in various cross sections of the Piave catchments has been examined in the cross sections where streamflow measurements are available. The minimum environmental flow within each reach of the Piave basin has been calculated by the Water Authority in 2001 as a prescribed percentage of the mean annual flow recorded, suitably manipulated on the basis of specific ecological and morphological reach–dependent parameters. Figure 8 shows the spatial distribution of the compliance percentage of the MEF resulting from the analysis of the available data. In Figure 8 red circles indicate the cases when the MEF is not guaranteed during more than the 50% of the time, while the green circles correspond to the cases where the MEF is complied with during more than the 90% of the observation period. The two maps reproduce the situations observed before the ratification of the prescriptions on the MEF (i.e., before 2001, Figure 8a) and after the ratification (i.e., after 2001, Figure 8b). The map shows that before 2001 the minimum flow was indeed not complied with downstream of the Vodo and Comelico reservoirs (sections 3 and 8), in the Piave river closed at Belluno (section 11) and in the Cordevole River closed at Sass Muss (section 16). After 2001, instead, we observe an expected increase of the MEF compliance percentage, in particular within the main reaches of the Piave river from Soverzene to Belluno.

The comparison of such results with the results discussed in section 4.3, however, suggests that, notwithstanding the compliance of the MEF, the effects of the regulation operations on the streamflow distribution downstream of the regulation are huge, with a drastic decrease of the mode and of the mean and a significant increase of the variability of streamflows (Figures 4 and 6 and Table 4). This clearly suggests the limitations inherent in the approaches based on minimum streamflow requirements. High com-

![Figure 8](image-url)

**Figure 8.** Compliance percentages of the minimum environmental flow (a) before and (b) after the introduction of rules on the minimum environmental flow. Numbers are listed in Table 2.
6. Conclusions

The following conclusions are worth emphasizing:

1. A novel approach has been developed and applied to analyze the impact of dam operations on the hydrologic regime of river basins. The approach focuses on the shape, the mode and the moments of the steady state seasonal streamflow pdf as indicators of the alterations induced by anthropogenic regulations on intra-annual streamflow variations. The prediction of the streamflow statistics that would have been observed in the absence of anthropogenic alterations is achieved by means of a stochastic analytical model which requires a suitable procedure of parameter estimation. The approach is deemed to be quite general in nature, and is particularly suitable to quantify the alterations induced by anthropogenic regulations in catchments where streamflow observations in the predisturbance period are lacking and/or important changes in the underlying climate regimes have been experienced. The methodology has been applied to the Piave river basin (Northern Italy), to evaluate the alterations of the streamflow regime observed in various cross sections affected by anthropogenic regulations;

2. The analytical model has been shown to accurately capture the observed streamflow statistics in unregulated subcatchments of the Piave basin. An objective procedure to estimate the model parameters from hydrologic, meteorologic and geopedologic information in regulated and unregulated catchments has been proposed. This allows for predicting the natural streamflow regime of 10 regulated cross sections of the Piave basin. A proper quantification of the alterations induced by anthropogenic regulations on the ensuing streamflow statistics has been thus achieved;

3. The observed pdfs downstream of the regulation devices have a smaller mean, a much smaller mode, a larger peak probability and a larger coefficient of variation than the pdf that would be observed in absence of anthropogenic regulations estimated by the model. The ratio between the mode and the mean in regulated sections is always smaller than that observed in natural conditions. In practice, the anthropogenic disturbance leads to a remarkable reduction of the overall water resources available during the summer, with an increase of the streamflow variability and an increase of the occurrence probability of preferential states far from the mean.

4. High compliance percentages of minimum streamflow requirements do not imply low disturbances of the streamflow regime. Thus, the lesson to be learned is perhaps that wiser water resources management strategies should be engineered by looking not only at the variations introduced on the exceedance probability of a given streamflow threshold (e.g., the MEF), but rather considering the disturbance introduced by anthropogenic regulations on the whole hydrologic regime of the river properly measured by the corresponding streamflow pdf.

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