Integrity Model Application: A Quality Support System for Decision-makers on Water Quality Assessment and Improvement

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Integrity Model Application: A Quality Support System for Decision-makers on Water Quality Assessment and Improvement

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Abstract. In this paper, a mathematical model has been applied to a river in North-East Italy to describe vulnerability scenarios due to environmental pollution phenomena. Such model, based on the influence diagrams theory, allowed identifying the extremely critical factors, such as wastewater discharges, drainage of diffuse pollution from agriculture and climate changes, which might affect the water quality of the river. The obtained results underlined how the water quality conditions have improved thanks to the continuous controls on the territory, following the application of Water Framework Directive 2000/60/EC. Nevertheless, some fluvial stretches did not reach the "good ecological status" by 2015, because of the increasing population in urban areas recorded in the last years and the high presence of tourists during the summer months, not balanced by a treatment plants upgrade.

1. Introduction

In recent years, increasing emergency situations have occurred regarding the availability of water resources in many countries, due to various reasons: high water demand by human uses and by the production sector, such as industry and agriculture; irreversible deterioration in surface water quality; saline intrusion of coastal aquifers; contamination of groundwater by nitrates; and presence of extreme meteorological events caused by climate change. Until several decades ago, water was considered to be an unlimited resource but nowadays it appears that the amount of water available is scarce and that the quality status of rivers, lakes and wet areas is definitely at risk and, in some cases, even irreversible.

These alarming conditions, which are mainly due to the use of surface water bodies as receptors of urban and industrial wastewaters, have forced the European Union to take action concerning water management by applying specific measures to help reduce growing pressure on waters from the population, industry and agriculture, such as: Directive 91/271/EEC concerning urban wastewater treatment, Directive 91/676/EEC on water protection against pollution caused by nitrates of agricultural source, Directive 98/83/EEC focused on safeguarding human health from adverse effects of any contamination of water, and Directives 76/464/EEC, 80/68/EEC, 82/176/EEC, 84/156/EEC, 85/513/EEC, 86/280/EEC, 91/414/EEC and 98/8/EC about the pollution caused by certain dangerous substances discharged into the aquatic environment.

However, increasing problems related to water quantity and quality led to the development of an integrated approach for water management systems, including all water-related impacts. These efforts resulted in the amendment of Water Framework Directive (WFD) 2000/60/EC, which is among the most progressive water-related regulations worldwide. In fact, it proposes an innovative attitude to water protection and management able to combine the identification of quality objectives, the monitoring of water bodies, the definition of intervention measures and the control of pressure sources from the surrounding territory. With regard to the last aspect, the WFD indirectly suggests using, at river level, a framework that works as a decision support model, able to design and plan interventions aimed at mitigating the pressure sources, with a view to reaching environmental quality objectives.

Therefore, in the present paper a Decision Support System named "Integrity model" was applied to a sample river, the Bacchiglione in North-East Italy, in order to reduce its vulnerability to the phenomenon of pollution. Such approach, besides representing an important support tool for local decision-makers when choosing effective mitigation actions, can also become useful to communicate the quality status of the river to the population in a fast and simple way [1], [2].

The model, previously developed in the same river in the period 2001-2003 [3], has now been recalibrated on a period of nearly 10 years (2007-2015). The obtained results, compared with the classification of water quality status carried out according to the criteria of both Italian Decree n. 152/1999 and Decree n. 152/2006 (adopting the WFD), demonstrated the reliability and accuracy of the model over a long period of time. It was also possible to verify its sensitivity to the changes occurred in the river during the last years, thanks to the application of the WFD. In particular, the continuous controls of the territory, which have reduced the presence of illegal discharge points, and a series of upgrades to the treatment plants have modified the vulnerability scenarios of the river and improved its status.

2. Integrity model

The Integrity Model is based on the theory of influence diagrams [4]-[6], which is a simple graphical representation of a group of arrows and nodes.

For each node, i, on the graph it is necessary to establish the level of functional integrity, which depends on the level of physical integrity, y_i, as well as on the level of functionality, $\overrightarrow{x_j}$:

$$\overrightarrow{x_j} = \overrightarrow{\varphi_i}\left(y_i, \overrightarrow{x_j}, j \in P(i)\right) \qquad (1)$$

y_i can be defined as a variable describing the physical condition of the node integrity, which has values between 0 and 1, where 1 indicates complete physical integrity and 0 its absence. The level of physical integrity is related to the stress vector, $\overrightarrow{\xi_i^k}$, through the vulnerability function, $f_i^k(\cdot)$, which is defined for each natural hazard k and for each node i of the territory considered, and it is expressed as $y_i = f_i^k \cdot \left(\overrightarrow{\xi_i^k}\right)$. The main role of this function is to provide a quantitative evaluation of the vulnerability level, which can be affected by a given stress caused by a natural hazard, k. In the present paper, the stress can be characterised, for example, by the flow of wastewater from treatment plants or by agricultural fertilizers reaching the water body after being washed off land.

In the simplest case, where the stress $\overrightarrow{\xi_i^k}$ may be a scalar quantity and described with a specific index, I, the level of physical integrity is simply a non–increasing monotonic function, included in the co–domain [0, 1]:

$$y_i = a\left(\frac{\exp(-\alpha I_i^2)}{1+\exp(-\alpha I_i^2)}\right) \qquad (2)$$

where the parameters a and α define the shape of the vulnerability function. Besides, the level of physical integrity, y_i, depends directly on its intrinsic functionality vector, $\overrightarrow{x_i^0}$, which describes the condition of the related node functional integrity: $\overrightarrow{x_i^0} = \overrightarrow{\rho_i}(y_i) \cdot y_i$. y_i does not consider the possible functional interconnection with other nodes. As for y_i, the intrinsic functional integrity can assume values between 0 and 1, where 1 indicates complete functional integrity and 0 the case in which the entity is non-functional.

The variable, $\overrightarrow{x_j}$, includes information related to the functionality of the other nodes that precede the node, *i*, and belong to *P(i).* It is clear that also $\overrightarrow{x_j}$ can assume values between 0 and 1, where 1 indicates complete functional integrity and 0 that the entity has broken down.

The function, $\overrightarrow{\varphi_i}$, which links the above-described variables, is generally quite difficult to define, as it requires detailed knowledge of the relationship between the different nodes. Generally speaking, it represents a problem in terms of optimisation [4], [5]. When analysing territorial problems affecting the loss of functionality (e.g., pollution risk), it is reasonable to consider the optimisation of equation (1). This can be done by looking into the conditions of minimum system functionality, and what represents the maximum risk for the territory.

Therefore, maximum vulnerability of the territorial system is obtained when each identified entity reaches a condition of minimum functionality. Assuming that the level of intrinsic functionality and of physical integrity of the node, *i*, and the level of functionality of each node belonging to *P(i)* can be expressed by scalar quantities, equation (1) can be presented as follows:

$$x_i = min\left(y_i, w_{ij}\left(x_j\right), j : e_j \in P(i)\right) \tag{3}$$

where the function $w_{ij}\left(x_j\right)$ takes into account the dependence level between the functionality of node *i* and node *j*. The identification of the mathematical structure able to represent the various dependences between the nodes is actually the most crucial step in the proposed model. In this paper, it can be assumed as a monotonic non–decreasing function, with domain and co–domain belonging to the range 0-1, according to [7]:

$$w_{ij} = \left(1 - 0.1\alpha_{ij}\right)\frac{\left(1-\exp\left(-\alpha_{ij}x_j^2\right)\right)}{\left(1-\exp\left(-\alpha_{ij}\right)\right)} + 0.1\alpha_{ij} \tag{4}$$

where α_{ij} is a parameter characterising the link (*i, j*) and it has been calculated in relation to the existent correlations between the entities *i* and *j*.

In this paper, in equation (2) the coefficients a and α were computed hypothesising three integrity classes, low (0-0.4), mean (0.4-0.8) and high (0.8-1), for each index [3]. In equation (4), instead, the parameter α_{ij} was evaluated assigning values of 2, 4, or 8 to it, according to the correlation between the index values of the nodes (weak, medium-strong and strong, respectively).

3. Discussion of results

The River Bacchiglione is located in North-East Italy (figure 1) and its waters flow into the Adriatic Sea. It borders to the southwest with the tributary reservoir of the Agno-Gua, to the West with that of the Adige and to the north-east with that of the Brenta.

The river has a length of 118 km and crosses two major cities, Padova and Vicenza, deeply marking their economy since ancient times. It is characterised by seasonal variation of the flows: generally high levels in winter and low levels in summer.

In order to apply the model, the river was represented into nodes and arrows. The nodes correspond to single quality gauge stations along the river Bacchiglione, managed by the Regional Environmental Prevention and Protection Agency of Veneto (ARPAV). The arrows are homogeneous stretches of the river, which link the nodes. The quality status of the single node (gauge station) was assumed as representative of the status of the whole arrow (stretch) associated to it.

3.1. Evaluation of stresses

The indices used here had previously been discussed in [3] and are the Non-Treated Loads index and the Total Pollutant Reduction index.

The Non-Treated Loads index measures those loads not provided by treatment plants and that reach the water body without any reduction. It is defined as:

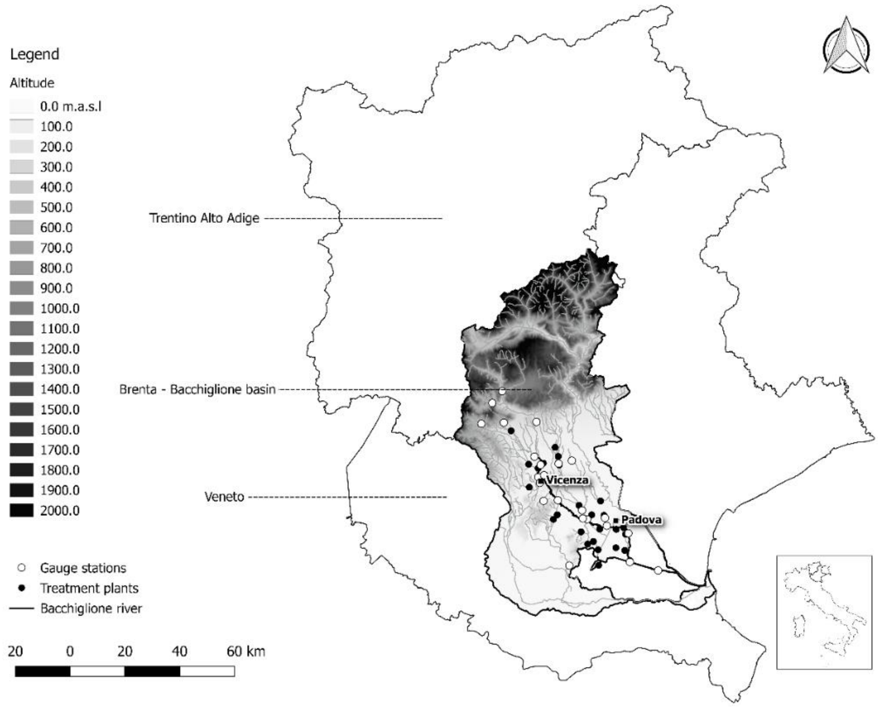

Figure 1. Brenta-Bacchiglione basin with gauge stations and treatment plants.

$$I_{NTL,COD} = 1 - \frac{\sum_{i=1}^{n} Q_{tr,p,i} c_{COD,i}}{Q_{R,j} \cdot c_{COD,j}} \tag{5}$$

where $Q_{tr,p,i}$ represents the flow rate discharged by the treatment plant, $c_{COD,j}$ is the *COD* concentration of each single discharge point, and Q_{Rj} and $c_{COD,j}$ are, respectively, the flow rate and the *COD* concentration measured at the downstream node of the fluvial reach to be analysed.

The Total Pollutant Reduction index allows evaluating the overall river response to the pollutant load and it is defined as:

$$I_{RED,COD} = \frac{Q_{R,i} \cdot c_{COD,i}}{P \cdot L_{SP,COD}} \tag{6}$$

where Q_{Rj} and $c_{COD,\mathrm{j}}$ represent, respectively, the flow-rate and the *COD* concentration measured at the node located downstream of the considered river reach, while $L_{SP,COD}$ is the *COD* load provided by each single equivalent-inhabitant, and *P* is the population of the sub-basin flowing into the node. $I_{RED,COD}$ estimates the extent to which the hydrological environment is able to protect itself from anthropic pollution loads insisting on the specific sub-basin.

Only the plants with a potentiality of more than 2000 Equivalent Inhabitants (EI) have been here considered, releasing more pollution loads and water flow. The project wastewater flow data were used and assumed constant for the whole period of study 2007-2015.

For the calculation of the $I_{RED,COD}$, the specific *COD* load produced by single equivalent inhabitant (inh.) was assumed equal to 100 g/inh a day and the population of the sub-basin flowing into the node was estimated according to the census by the National Institute for Statistics (ISTAT) from 2007 to 2015. The flow discharge in each gauge station was calculated using expeditive mathematical models based on the entropy theory [8,]-[12].

3.2. Evaluation of the functionality integrity level

The application of the integrity model to the River Bacchiglione allowed the identification of different vulnerability scenarios. Figure 2 shows the vulnerability scenario in 2009 before the WFD 2000/60/EC application.

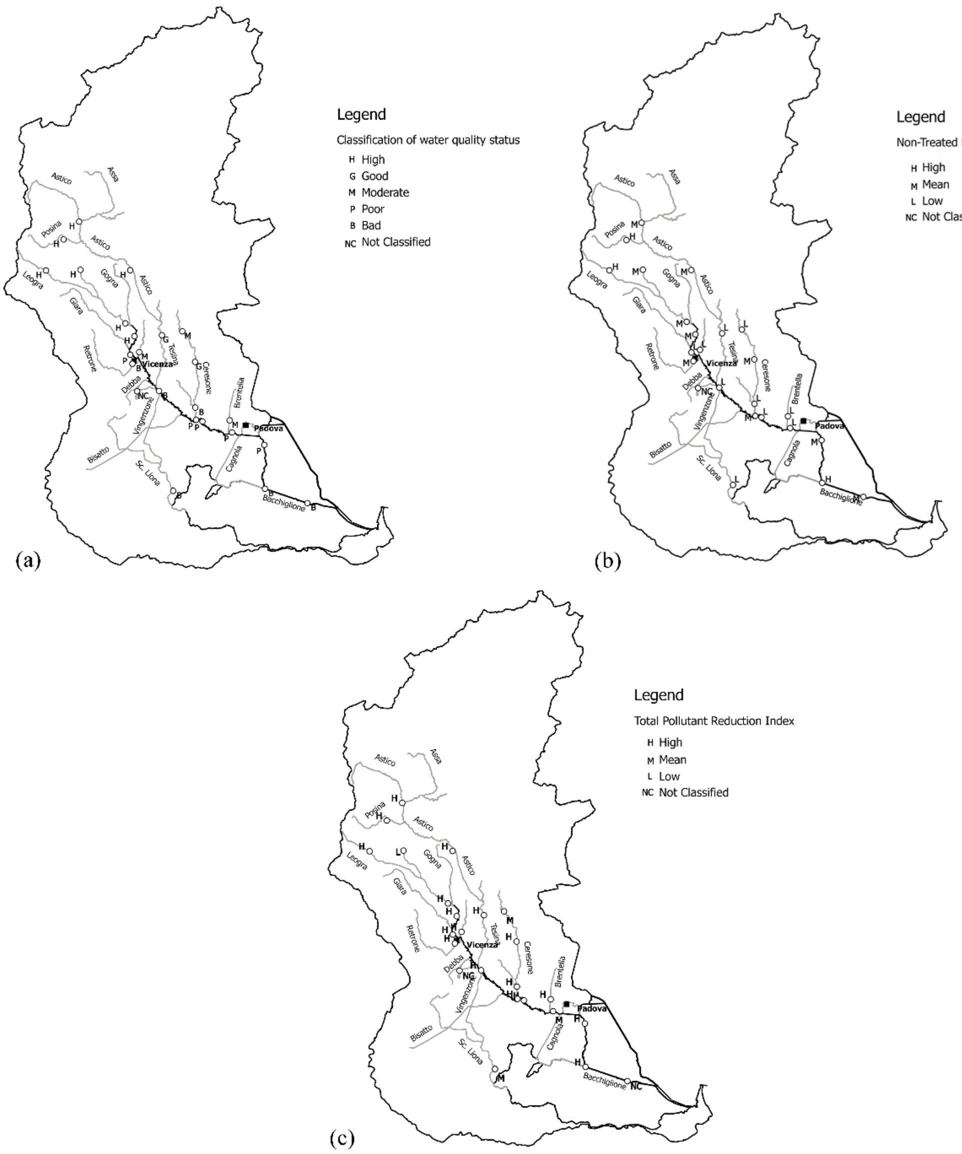

Figure 2. (a) Water quality classification according to Italian Decree n. 152/2006 (adopting the WFD); (b) level of functional integrity for the Non-Treated Loads index; (c) level of functional integrity for the Total Pollutant Reduction index (year 2009)

As represented by the figure, the upper part of the river is characterised by a "*High*" or "*Moderate*" quality status, also confirmed by the high values of the functional integrity level for both indices. Therefore, the good water quality recorded by ARPAV monitoring activities underlines the good auto-depuration capacity of the river and the absence of pressure sources from the surrounding territory. In the remaining part of the river and, in particular, in the fluvial stretch that goes from the gates of Vicenza to its mouth in the Adriatic Sea, the water environmental status changes and becomes "*Bad*" or *"Poor"*. The low functional integrity value of the $I_{NTL,COD}$ underlines the absent or inadequate treatment plants and the presence of unidentified discharge points along the river, while the high functional integrity linked to the second index, $I_{RED,COD}$, demonstrates the presence of civil pollution loads only. This vulnerability scenario is explained by the numerous small-scale wastewater treatment plants in the area, as well as by a strong diffuse urbanisation and industrialisation. Therefore, being the investigated stretches in a very critical environmental situation, the implementation of appropriate structural interventions is needed, such as wastewater collection, well-projected depuration systems and efficient disinfection equipment.

Figure 3 shows the vulnerability scenario in 2013, where the upper part of the river looks unchanged, while in the stretch near Vicenza the water quality has improved from a "*Moderate*" to "*Good*" status.

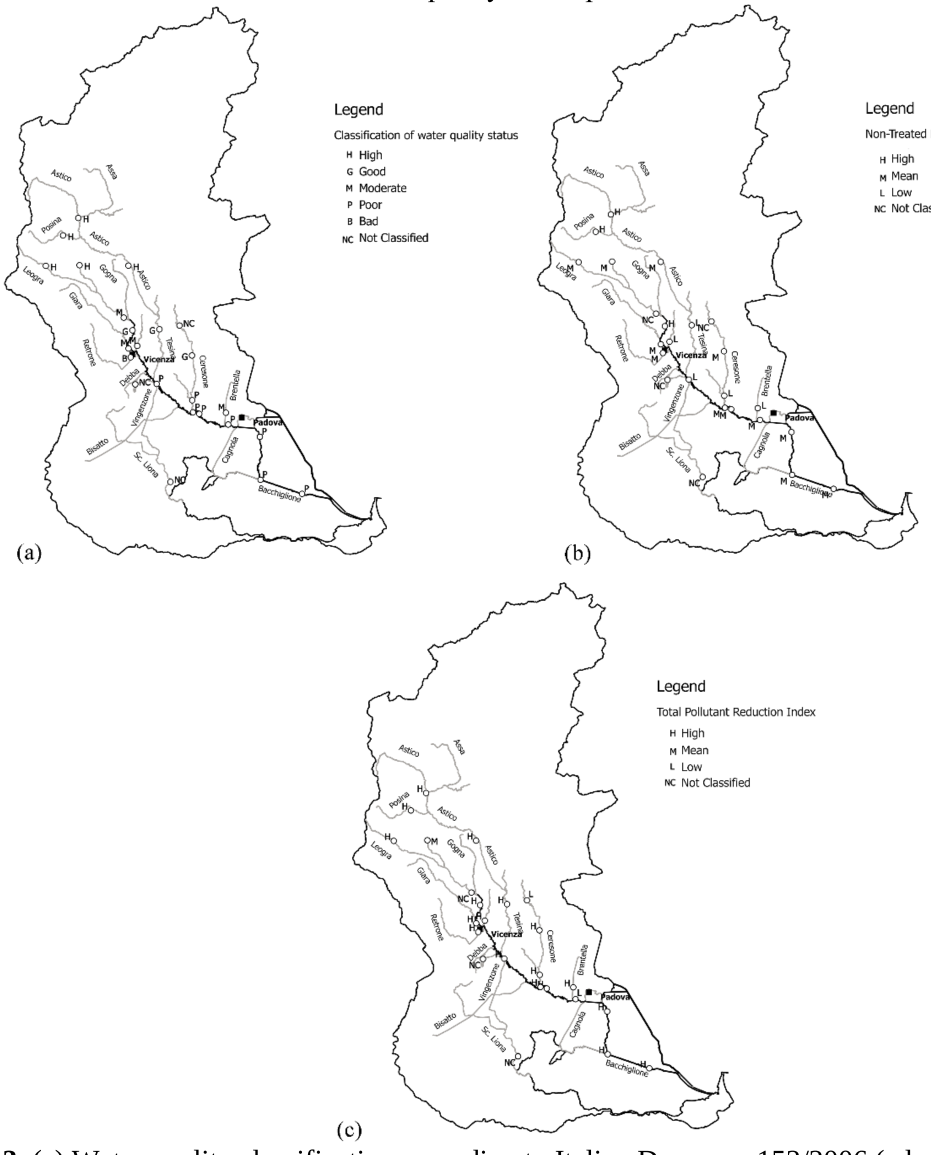

Figure 3. (a) Water quality classification according to Italian Decree n. 152/2006 (adopting the WFD); (b) level of functional integrity for the Non-Treated Loads index; (c) level of functional integrity for the Total Pollutant Reduction index (year 2013).

This is confirmed by high functional integrity for both indices. The WFD application to the river around 2010-2011, which led to a wide monitoring actions regarding the detection of non-controlled discharge points and to a series of upgrades of the treatment plants, has reduced the pollution phenomenon.

In the stretch that goes from the gates of Padova to its mouth, the situation is still very critical, as shown by the low functional integrity value of $I_{NTL,COD}$. In particular, despite continuous controls aimed at detecting and reducing the discharge points and different interventions on the treatment

plants, the river in its final stretch cannot mitigate pollution. This is also due to the increasing population in the last years and the high presence of tourists in the summer months.
Finally, figure 4 reports the vulnerability scenario of 2015, when all the rivers should have reached the "*Good*" quality status in compliance with the WFD.

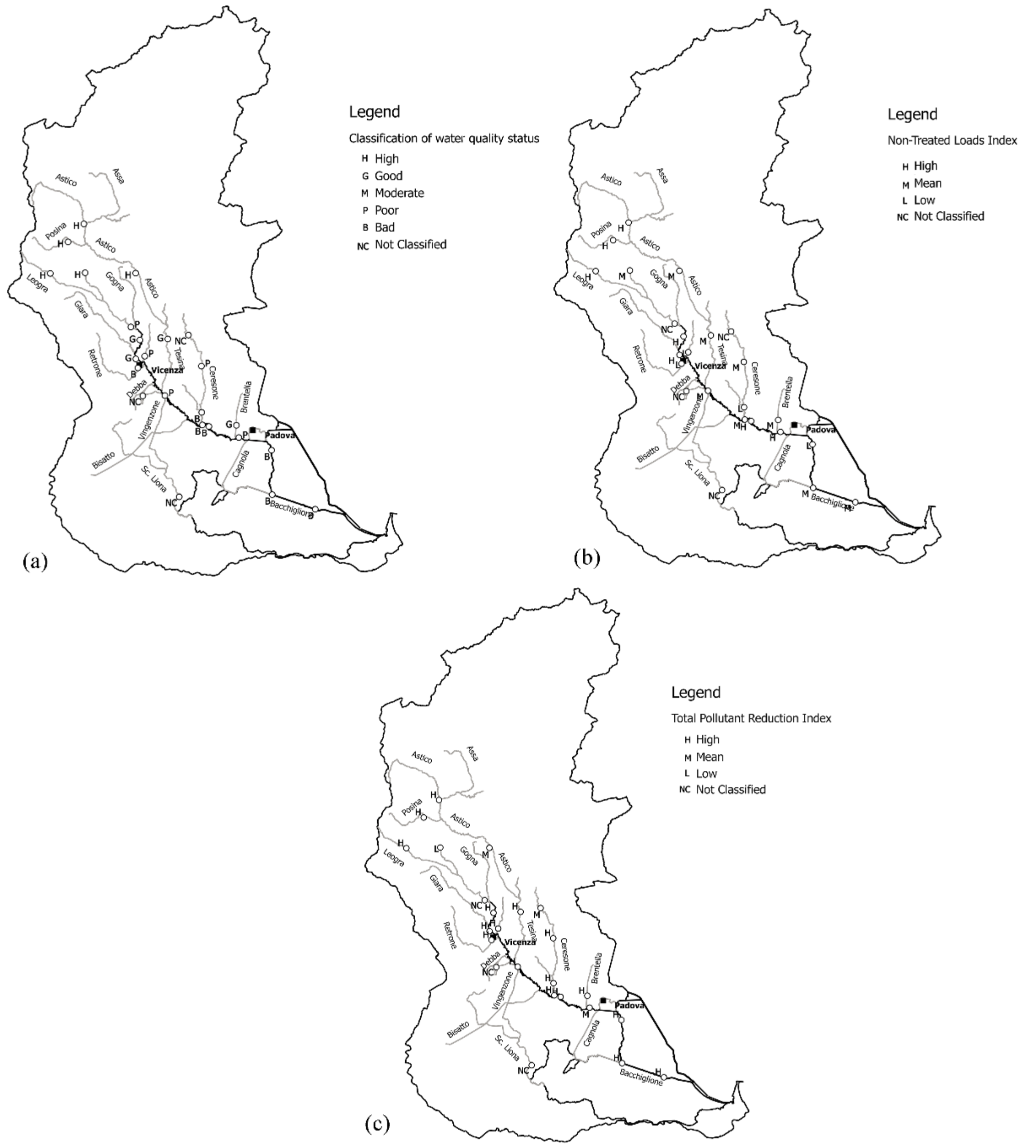

Figure 4. (a) Water quality classification according to Italian Decree n. 152/2006 (adopting the WFD); (b) level of functional integrity for the Non-Treated Loads index; (c) level of functional integrity for the Total Pollutant Reduction index (year 2015).

Actually, the status of the river has generally improved in nearly all the stretches and the values of both indices are high. Therefore, almost all the treatment plants have been correctly set, and the detailed monitoring activity has removed most of the illegal discharges and pollution loads from other sources. However, this must not distract from maintaining a policy of preventing and reducing the causes of pollution, in order to avoid the worsening of the water quality. The presence of stretches in a "*Bad*" or "*Poor*" status, such as the entrance to the city of Padova, should instead lead to a deeper control of the territory, aimed at reaching the "*Good*" water quality status.

4. Conclusions

The proposed model for the study of the River Bacchiglione vulnerability to the pollution phenomenon allows detecting the criticalities and the possible interventions needed to improve its water quality. Water body classification, performed according to the criteria of Italian Decree n. 152/2006, showed how not all the river stretches reached the "*Good*" status by 2015, according to the WFD.
The functional integrity evaluation of the Non-Treated Loads index underlined an improvement of the river water quality over the years, thanks also to the wide monitoring actions aimed at detecting illegal and incorrectly controlled discharge points, together with adjusting the treatment plants to the increasing population recorded in the last years. Only in some stretches, and in particular near Padova, the river still has a "*Bad*" status, which should lead to more actions and interventions addressing the pressure sources reduction.
The low values of the Total Pollutant Reduction index over the whole investigated period have instead demonstrated that the major causes of river deterioration are due to civil and industrial discharge points.
Therefore, the conclusions reached in this paper show how the integrity model, together with the existing classification systems for surface waters, can represent a useful and fast tool to support local technician and decision-makers when planning interventions and actions in order to mitigate the environmental pollution risk.

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