A fuzzy quality index for the environmental assessment of a restored wetland
E. Giusti, S. Marsili-Libelli and S. Mattioli

ABSTRACT
This paper describes the feasibility study for the restoration of agricultural land with a tendency to become waterlogged into a natural wetland, conceived to mitigate floods and to remove nutrients from the water drained from the cultivated plots. The wetland model, developed in aquatox, includes the nutrient dynamics both in the water and in the sediment, and the vegetation that is expected to develop as a consequence of flooding. The model inputs were synthesized from historical time series of rainfall and chemical data collected over the last decade. The model outputs are used to compute a synthetic fuzzy quality index (FQI) to assess the removal efficiency of the wetland. This FQI is based on three main variables describing the ecosystem quality: chlorophyll-a, dissolved oxygen and total suspended solids. This index has the merit of being simple enough to be immediately grasped by non-technical people, like managers and stakeholders, to whom the restoration project is proposed. The simulations, performed under five differing loading scenarios demonstrate the feasibility of this solution, which is robust enough to accommodate a 50% increase in either nitrogen, phosphorous or organic matter.

Key words | natural wetlands, fuzzy sets, artificial intelligence, water quality modeling, wetland modeling, simulation, AQUATOX

INTRODUCTION
This paper describes the feasibility study for the partial restoration of a historical natural wetland that was drained for agriculture. This project is part of an environmental improvement scheme of the area around the Massaciuccoli Lake, in central Italy (see Figure 1), a regional natural park surrounded by cultivated land that has a tendency to become waterlogged because its elevation is significantly lower than the lake. Figure 1 shows the extent of the subsidence and the location of the envisioned wetland. The wetland will cover an area of 26 ha and will drain a catchment of 700 ha.

The intense agricultural practice on the peaty soil, uncontrolled water abstraction and other hydrogeological mechanisms produce a ceaseless subsidence causing the land around the lake to sink at the rate of almost 1 cm per year. The level imbalance with the lake produces a considerable flow of water from the lake into the surrounding land, from which it is pumped back into the lake. In spite of the continuing efforts to keep the agricultural land dry enough for crops, the water table is steadily rising and it is estimated that in the coming decade the land use will undergo radical changes. Further, the pumping practice is being criticized as expensive, ineffective and contributing to the infiltration-subsidence cycle, in addition to returning a large amount of nutrients into the lake.

For these reasons partial wetland restoration is now being considered and this preliminary study assesses its nutrients removal efficiency. The modeling exercise includes three components: the synthetic input time-series, the wetland ecosystem model, and the definition of the fuzzy quality index (FQI).

TIME-SERIES SYNTHESIS
The behavior of the wetland model was simulated over a time-horizon of 7 years to allow for the ecosystem to settle, in particular for the biota to reach a reasonable steady-state. Two kinds of input time-series were synthesized: one for the flow and another for the water quality parameters.
Flow time-series

The flow into the wetland $Q_{in}$ is composed of the runoff flow originated by the rainfall $Q_{runoff}$ and the flow collected by the drainage ditches $Q_d$, a delayed consequence of runoff

$$Q_{in} = Q_{runoff} + Q_d.$$  

(1)

The former is a function of rainfall ($r$), the watershed area ($A$) and the runoff coefficient $C_d$ for which estimates in the wetland area $A$ are available (Di Grazia & Giannecchini 2008)

$$Q_{runoff}(t) = C_d \cdot A \cdot r(t).$$  

(2)

The rainfall is generated by two parallel modules: the first estimates the amount of rainfall for each wet day (Wang & Nathan 2007) whereas the second computes the succession of wet and dry days as a two-states Markov chain (Richardson 1981)

$$\rho_w = \rho_{wd} \cdot (1 - \rho_w) + \rho_{ww} \cdot \rho_w.$$  

(3)

where the probability of a wet day $\rho_w$ is a weighted sum of the probability that the present day is wet given a previous wet day $\rho_{ww}$ and that of a previous dry day $\rho_{wd}$. These wet/dry statistics $\rho_{ww}$ and $\rho_{wd}$ were computed on the basis of the observed precipitations in the years 1997–2007 (Di Grazia & Giannecchini 2008). From Equation (3) the total probability of a wet day is computed as

$$\rho_w = \frac{\rho_{ww}}{1 + \rho_{wd} - \rho_{ww}}.$$  

(4)

The amount of daily rainfall $r$ follows a Gamma distribution

$$f(r) = \frac{(r/\beta)^{\alpha-1} \exp(-r/\beta)}{\beta \cdot \Gamma(\alpha)},$$  

(5)

where $\alpha$ is a shape factor, $\beta$ is a scale factor and the Gamma function is defined as $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$ and its mean and variance are given by $\mu(r) = \alpha \beta^2$ and $\sigma^2(r) = \alpha \beta^2$. The drainage records obtained in the same years from Di Grazia & Giannecchini (2008), together

![Figure 1](image-url)
with the computed correlation between rainfall and drainage flow, were used for the computation of $Q_d$.

The wetland water volume $V_w$ is then obtained from the mass balance between input and output flow, where the outflow will be determined by artificial pumping depending on the wetland volume

$$\frac{dV_w(t)}{dt} = Q_{in}(t) - Q_{out}(t) = Q_{in}(t) - k_w \cdot V_w(t). \tag{6}$$

As a result of Equation (6) the hydraulic residence time varies between 5 and 20 days and the average water depth ranges between 0.2 and 0.8 m.

**Water quality time-series**

The model constituents are nutrients (ammonium-N, nitrate-N and phosphorus orthophosphate), organic matter (OM), and total suspended solids (TSS). The corresponding input time-series were synthesized on the basis of specific experimental data sampled by different authorities or researchers during the years from 1994 to 2007 (Baldaccini et al. 1997; Bonari et al. 1997; Cenni 1997; Mason 1997; Pensabene et al. 1997; Frascari et al. 2007; Baneschi 2009). Given the uneven sampling, time windows between one and three years were considered for creating the series, that were filtered with approximating splines for smoothing and missing data filling according to the following criterion

$$F(p) = p \cdot \left( \sum_{i=1}^{n} (y(i) - y_s(i))^2 \right) + (1 - p) \cdot \left( \int \left( \frac{d^2 f}{dt^2} \right)^2 dt \right). \tag{7}$$

The first term minimizes the squared differences between the data and the approximations, whereas the second minimizes the data ‘roughness’. The balance between the two depends on the smoothing factor $p$.

Sets of averaged monthly data were used as the basis for the synthesis. They were sampled in the drainage canals near the envisioned wetland area and smoothed with the criterion of Equation (7) as shown in Figure 2. Each variable was processed with an ad-hoc value of $p$ and then replicated over the simulation horizon of 7 years with an added 10% variability. Considering the runoff surface draining into the wetland, the minimum and maximum loadings obtained from the synthesized time-series are compared to other literature data in Table 1.

**MODEL PURPOSE AND STRUCTURE**

The restoration of wetlands is an expanding practice (Mitsch & Jørgensen 2004; Zhang & Mitsch 2005; White & Fennessy 2005; Kadlec & Wallace 2000) and mathematical

| Table 1 | Specific loadings in the base scenario, estimated from the time-series, compared to literature data |
| --- | --- | --- | --- |
| Total Nitrogen | 6.4–14.3 | – | 0.5–50 |
| Total Phosphorus | 1.1–2.4 | 0.2–6.3 | 0.1–5.0 |
| Suspended Solids | 500–886 | 19–1338 | – |

Units: (kg ha$^{-1}$ year$^{-1}$).

Figure 2  | Smoothing of the water quality data according to Equation (6) for the synthesis of the quality time-series. The basic yearly pattern is replicated over the simulation horizon.
modelling is a valuable tool in forecasting their characteristics. The AQUATOX platform (Park et al. 2008; Park & Clough 2009) was selected for this purpose given its ability to link water quality to aquatic life and its vast collection of animal, plant and chemical data from which a large variety of ecosystems can be modeled. AQUATOX has already been used to model wetlands (Koelmans et al. 2001; Sourisseau et al. 2008) and there are many applications reported in the literature, especially when an ecotoxicological risk assessment is required (Lei et al. 2008; Preziosi & Pastorok 2008; Rashleigh et al. 2009; McKnight et al. 2010).

This AQUATOX model includes the nutrient dynamics both the water column and in the sediment, modeled with an upper aerobic layer and a lower anaerobic layer. The sediment sub-model includes the processes of deposition and diagenesis (Di Toro 2001) and was adapted to this case using the information by Frascari et al. (2007). Based on local studies (Baldaccini et al. 1997; Bonari et al. 1997; Cenni 1997; Baneschi 2009), the phytoplankton community includes both blue-green and green algae, and the autochthonous macrophytes, Myriophyllum verticillatum L. and Elodea canadensis for their nutrient reduction capabilities (Ciurli et al. 2009). No attempt was made to model the upper layers of the trophic chain, as entirely hypothetical at this stage. The complete simulation scheme is shown in Figure 3.

**Simulation of the base and perturbed scenarios**

With the synthesized time-series the base scenario ($S_i$) was simulated over a 7-year horizon. Table 2 shows that the average removal efficiencies are in qualitative agreement with the literature, especially for the modest nitrogen removal in large free surface ponds (Hart 2006; Yeh & Wu 2009). Also, Sakadevan & Bavor (1999) observed considerable nutrient accumulation in the sediment, whereas frequent

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<td>TN</td>
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<td>TP</td>
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<td>11.0–22.7</td>
<td>11.0</td>
<td>48</td>
<td>13.0</td>
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<td>68</td>
<td>–</td>
<td>31.2</td>
<td>72</td>
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Figure 3 | Block diagram of the complete simulation model, showing the time-series generation section and the detailed AQUATOX wetland model. The input flow $Q_{in}$ feeds the volume $V_{in}$ dynamics which influences the reaction kinetics though the residence time. The quality data enter the chemical model through the water column.
cases of nitrate release from the wetland were also reported by Fisher & Acreman (2004).

To assess the robustness of the wetland model, four additional perturbed scenarios are defined in Table 3 together with the removal efficiencies, whereas Figure 4 compares the final year evolution of the model variables for all the scenarios. In the left plot the limited nitrification may be due to diagenesis and to the inhibiting effect of certain macrophytes, whereas the increased P uptake in summer and mid autumn is due to phytoplankton growth.

The right plot shows the evolution of the three variables on which the quality index will be based. The chlorophyll exhibits a large summer bloom and a smaller peak in October, for which the green algae are mainly responsible. The DO decreases in the spring due to the demand from the biota, then increases thanks to photosynthesis. The TSS fluctuates in spring and autumn as a results of variable rainy spells but remains fairly constant in summer for all the scenarios. In scenarios S2 and S4 nutrient overloading positively affects the chlorophyll during the summer bloom and consequently increases the DO.

Overall, the wetland model showed a satisfactory phosphorus removal due to plant uptake, whereas the poor or negative nitrate removal may be due to the inhibiting effect of some macrophytes, such as Elodea canadensis (Ciurli et al. 2009) and to the high photosynthetic oxygen production, limiting denitrification. Other instances of poor nitrate removal are reported in Cooper (2009) and in Table 2. The simulation results are in quantitative agreement with literature values (Hu et al. 2001; Braskerud 2002; Kieckbusch & Schrautzer 2007; Black et al. 2008) and in line with local data (Mason 1997; Pensabene et al. 1997) though no wetland system is available in the area for direct comparison.

Regarding the phytoplankton development, the observed concentration of nutrients put the wetland in the eutrophic

| Table 3 | Comparison of average removal efficiencies in the base case (S1) and in the alternate scenarios, computed over the final year of the simulation horizon |
|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Removal efficiency (%) | S1 base | S2 (S1 + 50% PO4) | S3 (S1 + 50% NO3) | S4 (S1 + 50% PO4 + 50% NO3) | S5 (S1 + 50% OM) |
| \( E_{\text{NH4}} \) | 40 | 17.9 | 19.5 | 15.5 | 7.7 |
| \( E_{\text{NO3}} \) | -53 | -67.8 | -40.3 | -36.2 | -93.0 |
| \( E_{\text{TN}} \) | 17.5 | 16.3 | 18.6 | 18.5 | 18.3 |
| \( E_{\text{PO4}} \) | 14 | 17.2 | 5.2 | 17.3 | -0.7 |
| \( E_{\text{TP}} \) | 28 | 28.2 | 24.8 | 28.2 | 26.8 |
| \( E_{\text{BOD}} \) | 61 | 62.6 | 62.6 | 62.7 | 63.6 |
| \( E_{\text{SS}} \) | 68 | 67.8 | 68.0 | 67.8 | 66.6 |
| \( E_{\text{TSS}} \) | 76 | 74.2 | 74.1 | 73.8 | 72.9 |

Figure 4 | Seventh year evolution of nutrients (left) and of the variables generating the FQI (right). The base scenario input is shown in light gray (red) and the dark gray (blue) lines refer to the five outputs scenarios. The circled numbers indicate some important transitions: (1) In S1, the NO3 _increase_ gives the blue-greens a competitive advantage over greens, with a decrease of Chl-a and DO; (2) In S2 and S3, the PO4 increase favors the greens with more oxygen production; (3) In S5 the OM increase produce more NO3 and PO4 resulting in more Chl-a and in an increased DO consumption; (4) The differing loading schemes influence the TSS only slightly during the summer months.
range and the simulated phytoplankton blooms in Figure 5 are in agreement with observations in the Lake Massaciucoli. The fact that the green algae often outcompete the blue-greens depends on a combination of environmental factors (nutrient loading, water depth, turbidity, etc.). The blue-greens prevail in the dry years with a lower nutrient loading, resulting from scarce precipitations. Figure 5 also shows the partition of nutrients during the base simulation with significant nitrogen accumulation in the sediments.

**DEFINITION OF THE FQI**

Synthetic environmental indicators based on fuzzy logic were preferred by Ganoulis (1994) for the ability to deal with information imprecision and the merit of reducing the data dimensionality. Later Chang et al. (2001) proposed a water quality index based on fuzzy clustering (Bezdek 1981) and a fuzzy similarity measure based on dissolved oxygen, pH, BOD and suspended solids. Another quality index based on fuzzy clustering (Liou & Lo 2005) compared well to the Carlson Trophic State Index (Carlson 1977). Ocampo-Duque et al. (2006) proposed an index based on the European Water Framework Directive indicators. The same directive motivated Munari & Mistri (2007) to propose FINE, a multi-metric, fuzzy-based index applied to Mediterranean transitional waters, later to be generalized in F-IND (Marchini et al. 2009). Finally, fuzzy inference systems similar to the one described here were applied by Jinturkar et al. (2010) to assess the quality of an Indian aquifer and by

![Figure 5](image.png)
Lermontov et al. (2009) to express the water quality in a Brazilian watershed. This brief survey demonstrates the broad application of fuzzy environmental indicators.

This FQI is based on dissolved oxygen, TSS, and chlorophyll-a. The algorithm is composed of fuzzification, inference, and defuzzification in that order (Takagi & Sugeno 1985) as shown in Figure 6. Fuzzification consists of translating numerical data into the degree of membership (DOM) with respect to a set of predefined functions, here labeled low, medium, and high, as shown in Figure 6. The fuzzy inference consists of a set of logical rules ($R_i : i = 1, 2, \ldots, n$)

$$R_i : \text{If } \{\text{DO is DO}_i \text{ and TSS is TSS}_i \text{ and Chla is Chla}_i\}$$

then $\{\text{FQI is FQI}_i\}$. (8)

in which the composition of the antecedents implies the consequent, defined in an arbitrary range $\text{FQI}_i = [1, 2, 3, 4, 5]$ with 1 representing the worst quality and 5 the best. The inference systems is composed of the ten fuzzy rules in Table 4, selected after testing many combinations and discarding the illogical ones. Finally, the FQI is obtained by defuzzification

$$\text{FQI} = \frac{\sum_{i=1}^{n} v_i \cdot \text{FQI}_i}{\sum_{i=1}^{n} v_i}.$$ (9)

where each FQI$_i$ is weighted by the consequent DOM $v_i$ resulting from the product composition of the antecedents in each instance of Equation (8), i.e.,

$$v_i = \mu_{\text{DO}_i} \times \mu_{\text{TSS}_i} \times \mu_{\text{Chla}_i}.$$ 

The index was evaluated for the five scenarios of Figure 4 and appeared to be most sensitive during July, so this monthly average was assumed as the quality estimator. Figure 7 shows the FQI evolution in the 7 simulated years and demonstrates the progressive improvement of the wetland. The
index discriminates among the scenarios, indicating that the wetland is negatively affected by an OM overload \((S_5)\) whereas nutrients overload \((S_3)\) has a positive effect.

**CONCLUSIONS**

This paper has presented a preliminary study for wetland restoration. The exercise consisted of three parts: the synthesis of the input time-series, the structuring of the free-surface wetland model and the definition of a quality index based on fuzzy logic to describe the wetland water quality. Though no comparison data are available for the area, the simulations show that the wetland can indeed improve the quality of the water received from the drainage channels, removing nearly one quarter of the incoming phosphorus and three quarters of the suspended solids, whereas nitrogen removal was less satisfactory. This last result may be explained with the contributions of the decomposing biomass and of the sediment flux. Regarding phytoplankton, the competition between blue-green and green algae was influenced by the climatic conditions, with the latter being favored in dry years characterized by a low nutrient input, but in the long run green algae are expected to dominate. In general, the wetland exhibited a considerable resilience to load increase and this is an important asset in view of accommodating possible overloads. The FQI proved adequate to describe the water quality and to compare several scenarios, showing that the mid-spring to mid-autumn period is the most critical and confirming, with its small variations, that the wetland is robust enough to withstand significant load fluctuations. Future work will be aimed at extending the model validity by adding more quality variables, improving the rule base, and expanding the paradigm of the scenarios.

**REFERENCES**


**Table 4**   Reference rules defining the FQI

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<td>{ (DO is DO(M) and (TSS is TSSL) and (Chla is Chla(L)) }</td>
<td>then (I) is (I_5)</td>
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<td>then (I) is (I_4)</td>
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<td>then (I) is (I_2)</td>
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**Figure 7**   Average July FQI for each scenario for all 7 years. The progressive improvement is apparent. The OM overloading \((S_5)\) adversely affects the wetland, which is hardly affected by nutrient overloading \((S_3)\).


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