WATER RESTORATION OF AN URBANIZED KARST STREAM BY FREE-WATER-SURFACE CONSTRUCTED WETLANDS AS MUNICIPAL WASTEWATER POST-TREATMENT

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The study was aimed at analyzing the effect of an increase of municipal effluent discharge quality on the water restoration of an urbanized karst stream, in order to define specific criteria and strategies to safeguard the water quality and to improve and control of the chemical characteristics of the effluent from municipal WWTP, prior to being discharged into the stream. A case study referred to an urbanized surface water body having locally a relevant role for nature, historical and social aspects, was examined. Water quality was examined in several scenarios in function of the treatment options. Wastewater discharge and water stream quality were verified by using models available in literature. Results showed a practical and real application of such a technology to the full scale.

Keywords: free water surface constructed wetland, low flow stream, urbanized watershed, water quality

1. Introduction

The issues related to the quality of surface water bodies and the strategies to be adopted for limiting the impact of the discharge of urban, agricultural and industrial effluents are extremely interesting. The impacts due to the discharges of civil and industrial wastewater are particularly important with respect to the receiving body and its auto-depuration capacity. Several studies analysed the anthropic influence on the quality of surface water crossing urbanized basins and the overall effects on the environment of the main pollutant load components [1,2]. In order to protect the quality of surface water and to prevent and reduce pollution, the restoration of water bodies by controlling the anthropic factors is crucial. Therefore, the correct management and operation of wastewater treatment plants (WWTPs) is very important. In a methodological approach, the

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development of monitoring networks, as well as modelling strategies, are fundamental tools for assessing actions for water protection [3-7]. The restoration actions at the watershed scale can be evaluated starting from the determination of the polluting load produced by urban and industrial areas.

Wetland systems represent an effective, economical and sustainable alternative to conventional treatment systems. They are particularly appropriate to produce an effluent suitable for irrigation or to be released into reciving water bodies. Free water surface constructed wetlands are widely used for various types of wastewater [8-10]. Wetlands are an optimal filter between aquatic and terrestrial environments.

The reduction of pollutants in a wetland is obtained by a complex interaction of physical, biological and chemical processes [11,12]. Several processes promote the removal of contaminants in typical constructed wetland such as sedimentation, biological degradation and sorption. Additionally, other more complex processes occur such as plant uptake, photochemical oxidation and phyto-volatilization, contaminant accumulation and metabolic transformation. The overall process is influenced by several factors: temperature, hydraulic and pollutant load, residence time, vegetation, water depth, shape and size of wetland. The decrease in temperature causes a reduction of reaction rates of biological processes and, consequently, lower yields of removal. It is possible that natural processes occurring in wetlands determine variable output concentrations, which require more attention in the control, design and management of plants. Literature reports pollutant removal rates [13,14]. For example, typical values of loading rate vary in the range of 4.5÷6 g m^2 d^{-1} for biochemical oxygen demand (BOD_5), 3÷7 g m^2 d^{-1} for total suspended solids (TSS) and 1.5 g m^2 d^{-1} for total Kjendal nitrogen (TKN). Surface loading range from 1,4 to 15 kg/ha/d. Numerous studies on wetlands systems showed the possibility to deplete nitrates to nitrogen gas by denitrification at low values of dissolved oxygen (DO) concentration, that are due to the presence of anaerobic soil layers or bio-films [15,16]. Some types of cations can precipitate phosphate under specific conditions. In particular, pH plays an important role. The phosphorous is normally present in the tissues of vegetal and animal organisms and it is necessary for their growth. Wetland provides phosphorous removal through sorption processes on soil. DO in wetland is consumed as a result of biological activity in sediments influenced by dissolved carbonaceous biochemical and nitrogenous oxygen demands. Overall, all decomposition processes in the wetland also contribute to COD and BOD, but consumption of dissolved oxygen is also related to micro-organism activities, plant and animal requirements for respiration and oxygen transfer from air and plant aeration. Plant aeration fluxes vary depending on the plant species and the support substrate, between values of approximately 1÷2 and 5÷6 g m^{-2} d^{-1}. The wetland ecosystem is rich in carbonaceous material contained in the biomass particulate or dissolved in the water column. The natural level of concentrations of the parameters as BOD_5, suspended solids, total nitrogen and total phosphorus, is not negligible [12]. Ammonia is below 0.5 mg L^{-1} and nitrates and total phosphorus below 0.1 mg L^{-1}. Some events, such as fluctuation in input flows and concentrations, weather conditions, animal and vegetation activities may reduce the approximation of this model for the simulation of pollutant removal. However, this model provides a reasonable approximation of performance for a wide range of pollutants and it is still considered as an appropriate design equation [17]. Several studies on the application of constructed wetlands showed a great potential for pollutant removal with a diversity of macrophyte types in subtropical and arid climates [18-20]. The feasibility of a constructed wetland concerns the location, the size and type of plant (free-water surface, FWS or sub-surface flow, SFW), pollutant removal, land availability, opportunity for modification of the receiving water body, and economic issues.

2. Materials and methods

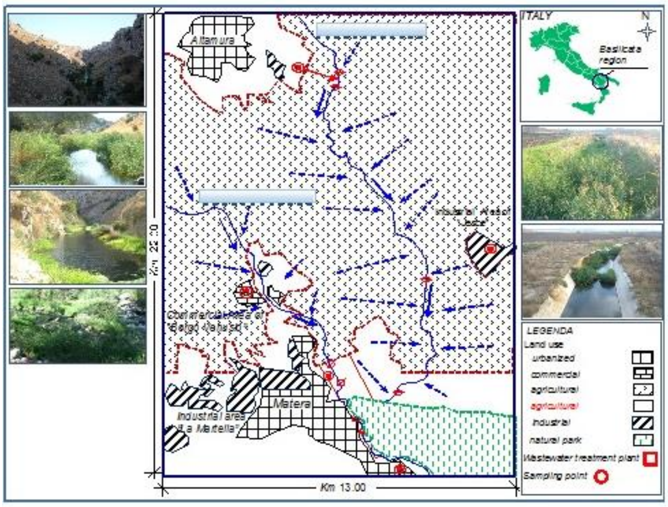
2.1 Area of study

The Gravina river (Fig. 1), flowing down in famous historical area (UNESCO World Heritage) close to Matera (Southern Italy, has as main tributary the Jesce river. The natural watershed, having a great tourist interest, is protected by the Murgia regional park. The stream runs through a catchment where urban, commercial and industrial activities influence the quality of a sensitive environment characterized by an extensive heterogeneity that promotes biodiversity. The basin has a surface of about 490 km^2 with a length of the main course of 27 km. The geological catchment is mainly constituted of clay materials. In the natural environment, the hydraulic sections are greatly variable; the narrow deep bed is characterized by an irregular altimetry, running along a fracture of calcareous-dolomitic banks. In the urbanized part of the basin, the bed sections are often adjusted with reinforced concrete slabs to form a typical trapezoidal section. The climate is arid, semi-dry. Water bodies show a stream-like regime, characterised by sudden floods due to short and intense rainfalls. In long dry periods, the stream water quality is mainly constituted by the municipal and industrial effluents and the flow decreases to low values (0.1÷0.6 m^3 s^{-1} with water heights of 0.1÷1.5 m).

The main municipal WWTPs operating in the basin, serve the towns of Matera and Altamura. Both the WWTPs have a secondary biological stage (activated sludge). The first discharges the treated effluent into the Gravina (60,000 equivalent inhabitants) and the second one into Jesce (70,000 E.I.).

Figure 1

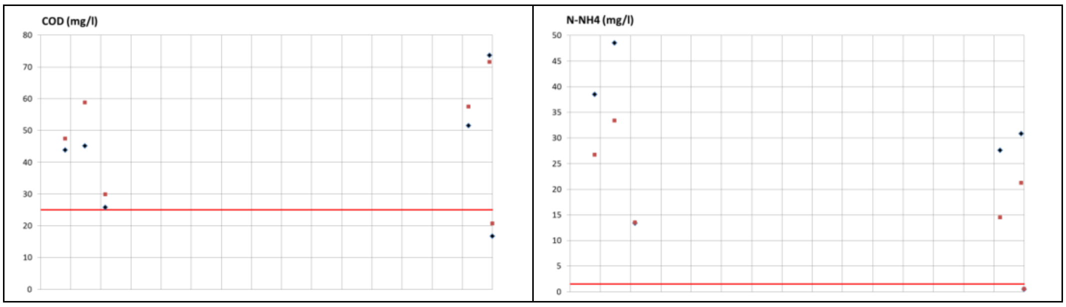
The watershed of the rivers in the urbanized areas of Matera and Altamura



2.2 Water quality analysis

Water quality was determined with several samples, collected in 6 sampling stations (4 along Gravina and 2 on Jesce river). The survey was carried out in a period of 150 days. Physical and chemical parameters, temperature, pH, electrical conductivity, DO, suspended solids (SS), chemical oxygen demand (COD), total nitrogen (TN), ammonia, nitrates, and orthophosphates, were measured according to Standard Methods [21]. Hydraulic flow data were measured too. An example of the results is shown in Fig. 2, where the samples were held on different days and at different sampling stages along Gravina river (km 0 is located 180 m downstream of the Jesce confluence).

In order to represent the stream water quality and compare different treatment scenario, the *WASP* model, version 7.52 [22], was applied.



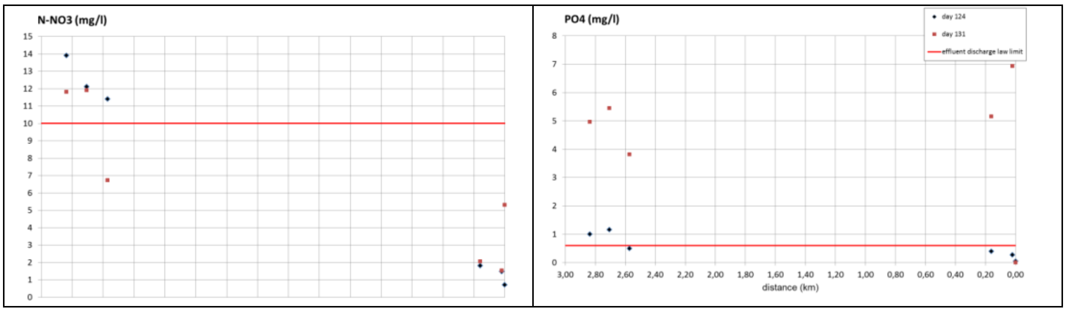


Fig. 2 Example of measured data of the Gravina water quality

Simulations were carried out considering temperature, DO, COD, ammonia and nitrate nitrogen. The calibration was based on data related to geometry of the river, headwater, plant discharges and measurements collected in the monitoring survey. The main assumed kinetic parameters are summarized in table 1, while the re-aeration process was calculated with the *O'Connor-Dobbins* formula [23].

Table 1

Kinetic parameters

Parameters	unit	Value
Slow BOD hydrolysis rate	d^{-1}	0.4
Fast BOD oxidation rate	d^{-1}	3.2
Organic nitrogen hydrolysis rate	d^{-1}	0.2
Nitrification rate for ammonia	d^{-1}	1.2

The hydraulic network was build up assuming that the Gravina stream and its main tributary, Jesce, have lengths of 3 and 22 km respectively. The two streams were subdivided into 75 reaches, characterized in function of the main riverbed parameters (slope, bottom width, roughness). The stream sections were represented with a trapezoidal or a triangular shape. Water flow was analysed considering two hypothesis of dilution of wastewater flow (low and flood conditions, Table 2).

Table 2

Flows (m^3 s^{-1}) hypothesis

Flow regime	Dilution rate	Average flow		WWTPs effluent	
		Gravina	Jesce	Matera	Altamura
I	1:10	0.012	0.015	0.120	0.150
II	1:1	0.120	0.150	0.120	0.150

2.3 Scenarios analysis

In order to evaluate the quality state of Gravina and Jesce, three scenarios (A, B, C) were considered (Tab. 3):

- A: current situation

- B: upgrading of both the WWTPs in order to meet compliance with the discharge limits, with (case 2) and without (case 1) addition of a FWS constructed wetland upstream of the discharge in the hydraulic receptor
- C: tertiary chemical stage, with (case 2) and without (1) reuse in agriculture.

The quality of the treated effluent (Tab. 4) to be considered in the various scenarios has been set according to the following table, in which the regulatory limits are fixed by Italian law (Leg.D. no. 152/2006). In order to compare the effects of the different operative hypothesis, the water quality classification was evaluated by using four conventional quality states (Tab. 5).

Table 3

Different scenarios

Operative condition		A	B		C	
			1	2	1	2
effluent quality	out of law limits	X				
	according to law limits		X	X	X	X
tertiary treatment	none	X	X			
	FWS wetland			X		
	advanced				X	X
disposal	Gravina	X	X	X	X	
	no discharge; total reuse					X

Table 4

Water quality of the municipal effluents

Pollutant	Parameters	unit	Municipal effluent		Treatment effluent	
			according to law limits (B1)	out of law limits (A)	FWSCW effluent (B2)	advanced treatment (C1, C2)
Organic Matter	BOD	mg L^{-1}	25.0	125.0	15.0	10.0
Macro-nutrient	total nitrogen	mg L^{-1}	15.0	30.0	12.0	10.0
	ammonia	mg L^{-1}	4.5	15.0	3.0	3.0
	nitrate	mg L^{-1}	8.0	5.0	2.0	7.0
	total phosphorus	mg L^{-1}	1.5	5.0	3.0	1.0

Table 5

Classification of riverine water quality

Pollutant	Parameters	unit	good	moderate	poor	bad
Organic Matter	BOD	mg L^{-1}	< 1.5	1.5 ÷ 2.0	2.0 ÷ 5.0	> 5.0
Macro-nutrient	Total nitrogen	mg L^{-1}	< 2.0	2.0 ÷ 5.0	2.0 ÷ 5.0	> 10.0
	ammonia nitrogen	mg L^{-1}	< 0.06	0.06 ÷ 0.12	0.06 ÷ 0.24	> 0.24
	nitrate nitrogen	mg L^{-1}	< 0.6	0.6 ÷ 2.4	2.4 ÷ 4.8	> 4.8
	total phosporus	mg L^{-1}	< 0.05	0.05 ÷ 0.1	0.1 ÷ 0.2	> 0.2

2.4 FWS constructed wetlands (scenario B2)

The FWS constructed wetlands plants (CWPs) (Fig. 3) were located downstream of the WWTPs, able to treat all the effluent from the WWTPs.

Available land was localized in two areas with a surface of 10.5 ha and 12.5 ha respectively. The depth of the basins was fixed at 0.5 m. Average daily effluent flow rates were estimated at 13,475 m^3 d^{-1} and 15,275 m^3 d^{-1} respectively.

Fig. 3 Location of the CWPs before the discharge in Gravina (a) and Jesce (b)

In order to manage the loading rates, to adapt different inflow water quality, to maximize the utilization of the area, minimizing the hydraulic short circuits, multiple flow paths were designed. The wetland basin was sub-divided in channels and cells through the creation of ponds in series and in parallel, in order to meet performance and maintenance requirements (replanting, harvesting and rodent control). Three configuration of the CWPs were considered for the lay-out process (Fig. 4): single channel (a), parallel channels with multiple inlets and flow control berms (b) and provided with separation dikes (c).

The configurations of the CWPs were analysed as:

- a single Plug-Flow Reactor (PFR)
- a series of Continuous Stirred Tank Reactor (CSTR)

The removal of pollutants has been determined by evaluating the effluent concentration using the equations reported in literature [12], and in particular, adopting the basis equations of *Reed*'s model [24], where the removal efficiency of the total phosphorus was calculated the expression proposed by Crites et al. [25]. The dimensioning of the CWPs was made considering a hydraulic load rates of 125 mm ha^{-1} d^{-1}, an organic load of 30 kgBOD ha^{-1} d^{-1}, a nitrogen load of 19 kgN_{tot} ha^{-1} d^{-1} and a phosphorus load of 2.5 kgP_{tot} ha^{-1} d^{-1} [19].

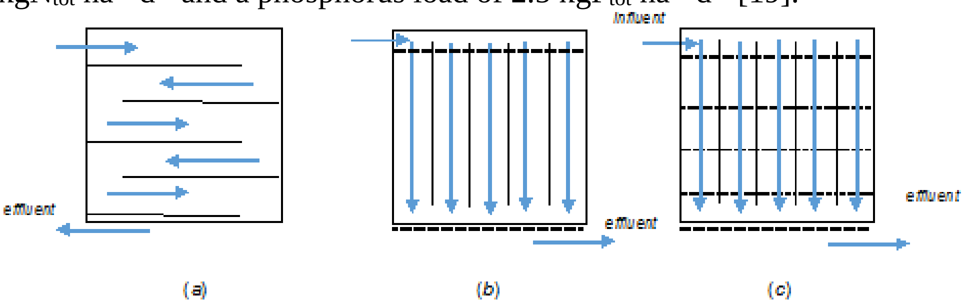


Fig. 4 Different lay-outs of the CWPs

3. Results and discussion

3.1 Observed water quality

The Gravina downstream the municipal discharge of Matera WWTP up to the confluence with Jesce

The pollutant concentrations usually increase with respect to the concentrations measured upstream the discharge. Values vary in ranges from 16.7÷20.7 to 51.5÷73.6 mg L^{-1} for the COD, from 0.50÷0.52 to 14.5÷30.8 mg L^{-1} for ammonia nitrogen. Electrical conductivity shows a sensible reduction, with values included between 733 and 967 µS cm^{-1}. Immediately downstream the discharge, we observed a nearly instantaneous decrease in the concentration of dissolved oxygen evidently due to the mixing of waters with greater flows characterised by lower concentration values. The dilution and concentration processes of pollutants are strongly affected by the water flow discharged by the treatment plant, which constitutes most of the water outflow of the riverbed during dry periods. Far from the discharge, a restoration of qualitative conditions was observed with a decrease of the concentration of pollutants, due to the diffusion and re-aeration of water. The COD decreases downstream. Upstream the confluence with Jesce river, the DO tends to decrease. This is evidently connected to the degradation of biodegradable organic matter associated to the secondary effluents, both in particulate and soluble forms. The average rate of oxygen consumption is about 0.02 mg $L^{-1}m^{-1}$. The contextual reduction of ammonia concentrations with the increase of nitrate nitrogen indicates the development of nitrification processes.

The Jesce downstream the municipal discharge of Altamura up to the confluence with Gravina

Downstream the discharge of the WWTP of Altamura, the water shows the worst quality; the COD values reach 95.6 mg L^{-1}, ammonia nitrogen stabilizes at 57.7 mg L^{-1}. Conductivity shows values in the range 1123÷1182 µs/cm. DO shows a remarkable decrease; low levels are also recorded downstream of the industrial area of Jesce, with concentrations next to 1÷2 mg L^{-1}. The average rates of oxygen consumption are between 0.01 and 0.02 mg $L^{-1}m^{-1}$. We noticed a re-oxygenation of the waters further downstream and near the confluence with the Gravina; this was due to the adjustment of a large-section of the river-bed and the hydraulic falls formed by the natural course of the stream. The average rates of oxygenation are between 0.001÷0.003 mg $L^{-1}m^{-1}$. The COD is almost constant downstream, except for a reduction in the stretches where hydraulic falls make its effect evident. Just after the WWTP, ammonia nitrogen remains substantially constant, as well as the nitrate nitrogen. In the following stretches we observed a slight reduction in ammonia and an increase of nitrate. Electrical conductivity remains steady with values between 1152 and 1156 µS cm^{-1} in the central and end courses.

The Gravina downstream the confluence with the Jesce

Downstream the confluence with the Jesce, we found remarkable increases in the values of pollutant parameters: the COD varied from 25.8÷29.9 to 43.8÷47.4 mg L^{-1} and ammonia nitrogen from 13.4÷13.5 to 26.7÷38.5 mg L^{-1}.

Small changes of electrical conductivity were observed. As far as DO is concerned, we observed a re-oxygenation favoured by mixing with the waters of Jesce characterised by a higher concentration having crossed the natural falls before the confluence. In the water courses where re-oxygenation was observed, the aeration rates were calculated in a range 0.001÷0.006 mg $L^{-1}m^{-1}$; whereas the consumption rates of oxygen varied between 0.02 ÷ 0.12 mg $L^{-1}m^{-1}$.

3.2 FWSCW design

Design of wetlands is based on empirical models and formulations that require the knowledge of specific factors. The size of the plant could be influenced by morphological criteria, nature and permeability of soils. In some arid areas, evapo-transpiration may have an important role in the hydraulic balance, affecting technical and economic aspects. The choice of the plants needs a deep knowledge of climate, latitude, potential for growth and maintenance. *Phragmites*, *Typha* and *Scirpus* are commonly used. The design of the constructed wetlands has carried out, once the morphology and the hydraulics of the basin have been fixed, by applying empirical factors. In order to determine the plant surface, parameters mainly include hydraulic retention times (HRT) and removal factors of pollutant load, in function of flow rate, influent concentrations and sizes. Figure 5 shows the connection between surface demand and pollutant removal.

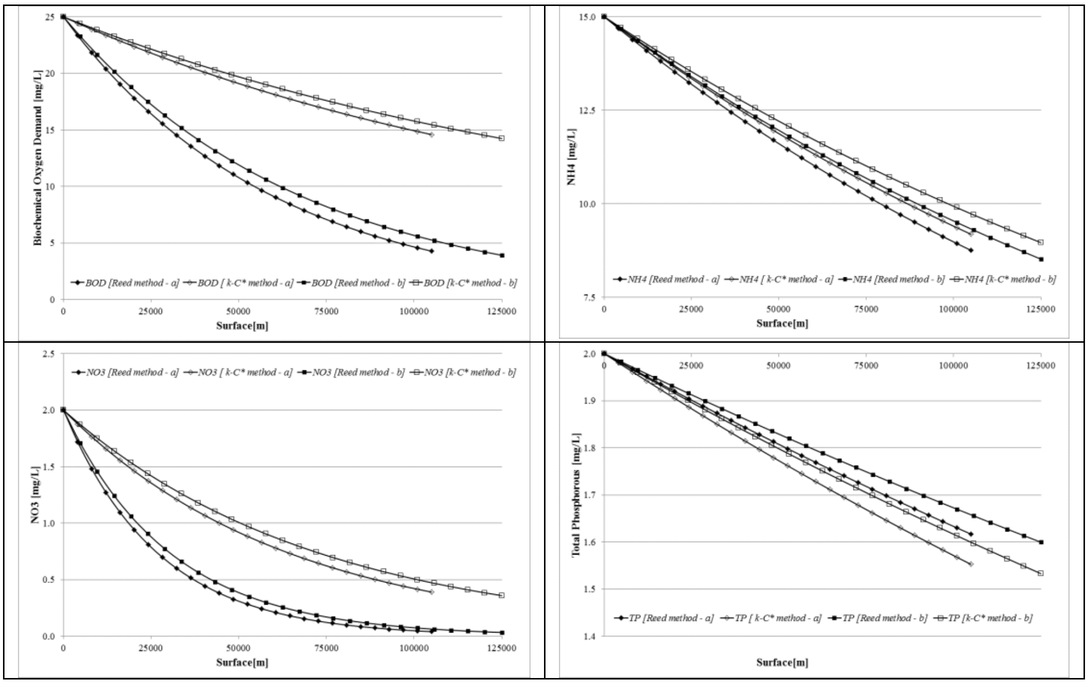


Fig. 5 Pollutant concentration and required area for FWS

3.3 Comparison of scenarios

The simulation output supplied by WASP model, presented a very good correspondence with the measured water quality data. The simulation was also useful in estimating the state of a long stretch of the Gravina river, for which it was not possible to acquire measurements due to the adverse morphology of the riverbed. The model allowed to consider and to compare the different operative scenarios, obtaining the correspondence level of quality related to each technical solution (Tab. 8).

Table 6

Expected water quality related to the different scenarios

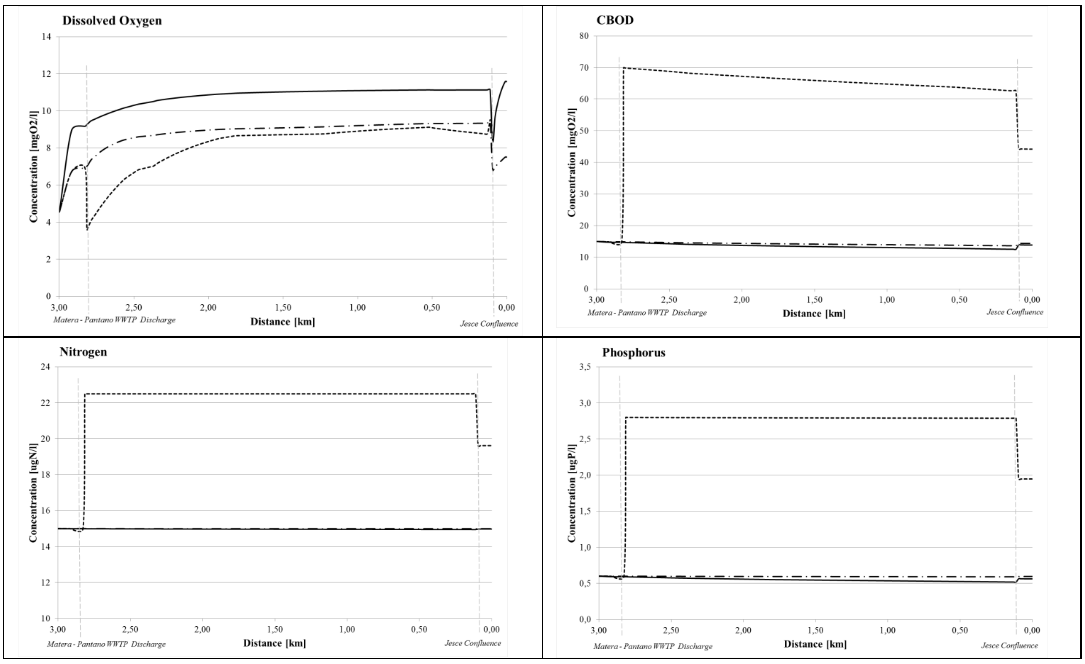
Flow	A	B		C	
		1	2	1	2
I - low water	bad	bad	moderate	moderate	good
II - flood	moderate	poor	moderate	good	good

In the current situation (scenario A), both of the effects of the discharges of the municipal effluents of WWTPs are evident. Downstream the WWTP, the water of the Gravina shows a decrease of DO and increasing value of COD and ammonia nitrogen. After the confluence of the stream Jesce, the analysis demonstrates an increase in the concentrations of COD and ammonia caused by the bad quality of water in the river Jesce (that also receives not treated wastewaters, illegally discharged).

The scenario B represents the situation relative to the performance of WWTPs according to the law requirements (B1), while B2 presents, in addition to B1, the insertion of the FWS downstream the WWTPs. The presence of wetland is important to improve the water quality, in particular in condition of flood flow. The better scenario, obviously, is the third one with a tertiary chemical stage applied as final step. Moreover we have to consider this scenario, as the most significant under the economic point of view. The main observations are:

- there is a dilution of pollutant in the water of the Gravina river, at the confluence, due to the fact that the flow rate of incoming Jesce is greater;
- concerning to the oxidation rate, the lowest values reported in literature do not allow to represent the path of stabilisation of biodegradable organic matter; so that, the higher values represent suitably such a process;
- considering the nitrification rate, the highest values does not allow a good representation of the more intensive observed increase of nitrate and oxygen concentration up to 60÷70 % of saturation rate.

Figure 6 shows the simulations of the water quality for Gravina river.



Legend: scenarios A …... scenario B _._._. scenario C ____.

Fig. 6 Simulated data of the water quality along the Gravina stream

4. Conclusions

A specific project analysis was analysed with the aim at safeguarding the surface water quality of the *Gravina river* stream in the urbanized area of Matera (*Southern Italy*). A survey was carried out to evaluate the basic elements of planning action. The negative effects of water pollution originated by the anthropic pressure and different land uses are widely evident in the watershed.

The treatment of municipal secondary effluent with FWS constructed wetlands can represent an effective solution. This system, if integrated in a methodological restoration strategy, allows a reduction of the environmental impact and an improvement of the river water quality.

An improvement of the water quality could mainly be obtained through the control of the discharged polluted flow from urbanized watershed and agricultural and industrial areas, during both dry and rainy periods.

The results show a good applicability of FWS constructed wetlands to pollution control of the discharge of the municipal treatment plant. Model simulation results allowed a good representation of the observed water quality data and simulated restoration actions, even though they resulted from applied values of specific parameters with several limitations.

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