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Technical note

Water quality control in the river Arno

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Abstract

In this work, we analyzed pollution in the river Arno using a non-steady advection–dispersion–reaction equation (ADRE) calibrated on experimental data. We examined the influence different pollution control strategies have on dissolved oxygen (DO). We considered (i) flow rate variation; (ii) local oxygenation at critical points; (iii) dynamic modification of wastewater load. Results indicate first, that reservoir management is effective in reducing pollution; second, that local oxygenation is necessary to ensure that DO does not fall below safety levels; and finally, that tuning wastewater loads appears to be impractical to manage the river quality given the stringent limitations it would impose on the industrial effluents. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Arno; Water quality modelling; Water quality control; Advection–diffusion–reaction equation

1. Introduction

Pollutant species from agricultural and farming activities, untreated urban sewage and industrial effluents driven into the river by wastewaters or surface runoff can be the cause of severe pollution. Threshold values for pollutant load in wastewater, established independently of the river flow rate, do not protect from pollution since the mechanisms which determine water quality are mixing, transport and species reactions occurring in the receiving water body. This is apparent in low-flow periods, when the assimilative capacity of the river is reduced. The level of dissolved oxygen can fall below safety thresholds which prevent the anaerobic conditions and are essential for the survival of aquatic species. To maintain pollution below a given threshold, the assimilative capacity of the river should remain sufficient to comply with the current pollution load all along the river. This goal can be achieved (i) by controlling the river flow rate [1] and (ii) by controlling the wastewater pollution load [2]. To control the river flow rate, we need first accurate hydraulic models coupled with accurate prediction of runoff, recharge and dam discharge [3,4]. Then, strategic use of reservoirs management can be planned to enhance mixing efficiency, transport and reaction—i.e. the natural pollution remediation mechanisms of the stream—that strongly depend on the flow rate. This choice is effective for most pollutants but has no significant effect on dissolved oxygen (DO), the balance of which is governed by complex dynamics. DO level could be increased locally using weirs or oxygenators. Controlling and tuning wastewaters pollution load may also be effective, provided that an accurate model of the river water quality is developed. The effectiveness of approaches (i) and (ii), single or combined, depends on the river system considered. In this paper, we evaluate both approaches for the river Arno, the conditions of which require a timely action.

Water quality in the river can be modeled using various approaches: time-series statistical analysis [5], neural network functional approximation [6] or mass-balance equations [7]. We use an Advection–dispersion–reaction equation (ADRE), coupled to a transient hydraulic model, similar to previous works [8]. We

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Nomenclature

A	flow section of the river
c	water heat capacity
C	species concentration
D	species dispersion coefficient
D_m	molecular diffusion for oxygen in water
g	gravity
h	water level
H_N	net energy flux through the air–water interface
k_1	rate of degradation of BOD
k_2	reaeration coefficient
L	BOD concentration
n	Manning coefficient for roughness
O	oxygen concentration
O^*	oxygen concentration at saturation condition
Q	flow rate
R	hydraulic radius
S_0	longitudinal slope of the bottom
t	time
T	water temperature
x	curvilinear coordinate along river axis
W	width of the section at the free surface
α_3	rate of oxygen production per unit of algal photosynthesis
α_4	rate of oxygen uptake per unit of algae respired
μ	algal growth rate
ρ	algal respiration rate
ρ_w	water density
σ	algal deposition rate

calibrated and validated the model using data collected on the site during different experimental campaigns and we used it to evaluate alternative strategies for water quality control.

2. Data and methodology

2.1. Site and data

The reach of the river from Nave di Rosano to S. Giovanni alla Vena we considered—about 89 km long—is a highly polluted area; industrial wastewaters from manufacturing districts add to untreated civil wastewaters from Firenze and other cities along the river, determining a potential threat to the environment. Fig. 1 shows a map of the site. The straightened path with tributaries, wastewaters and uptakes (above) and measuring sections (below) are shown in Fig. 2(a).

Three experimental campaigns used for validation were made in July 1995, October 1995 and March 1996, to examine the river quality in different seasons [9]. The campaign of July 1996, reported in Table 1, was used as a starting point to evaluate different alternatives for water quality control.

Water quality is determined by pollution carried by tributaries and wastewaters, and by water quality and flow rate at Nave di Rosano, the upstream section. Flow rate and water quality measurements were taken on-site for tributaries, wastewaters and for specific locations

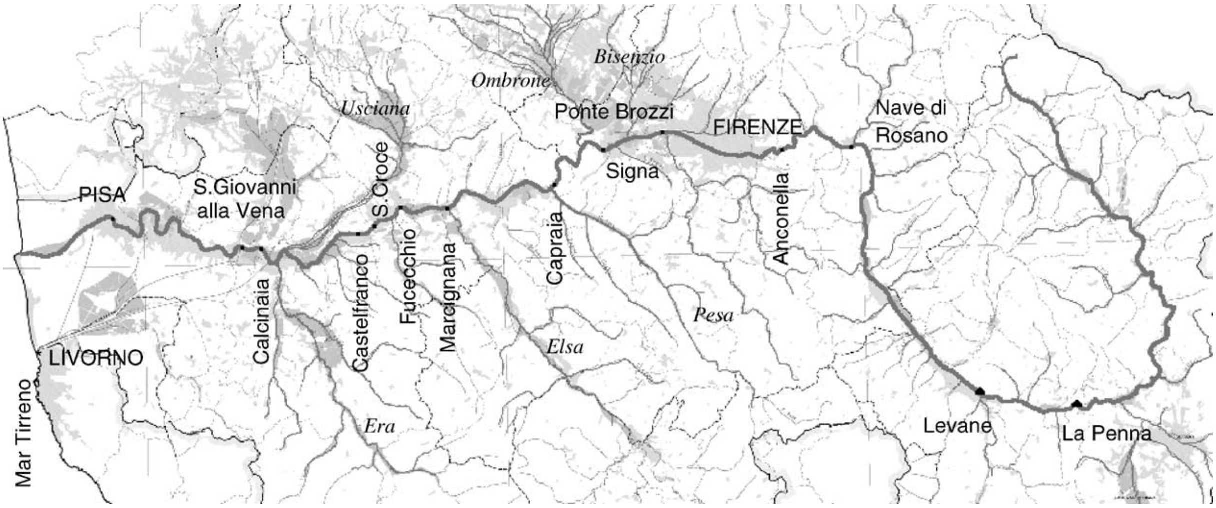

Fig. 1. Map of the site.

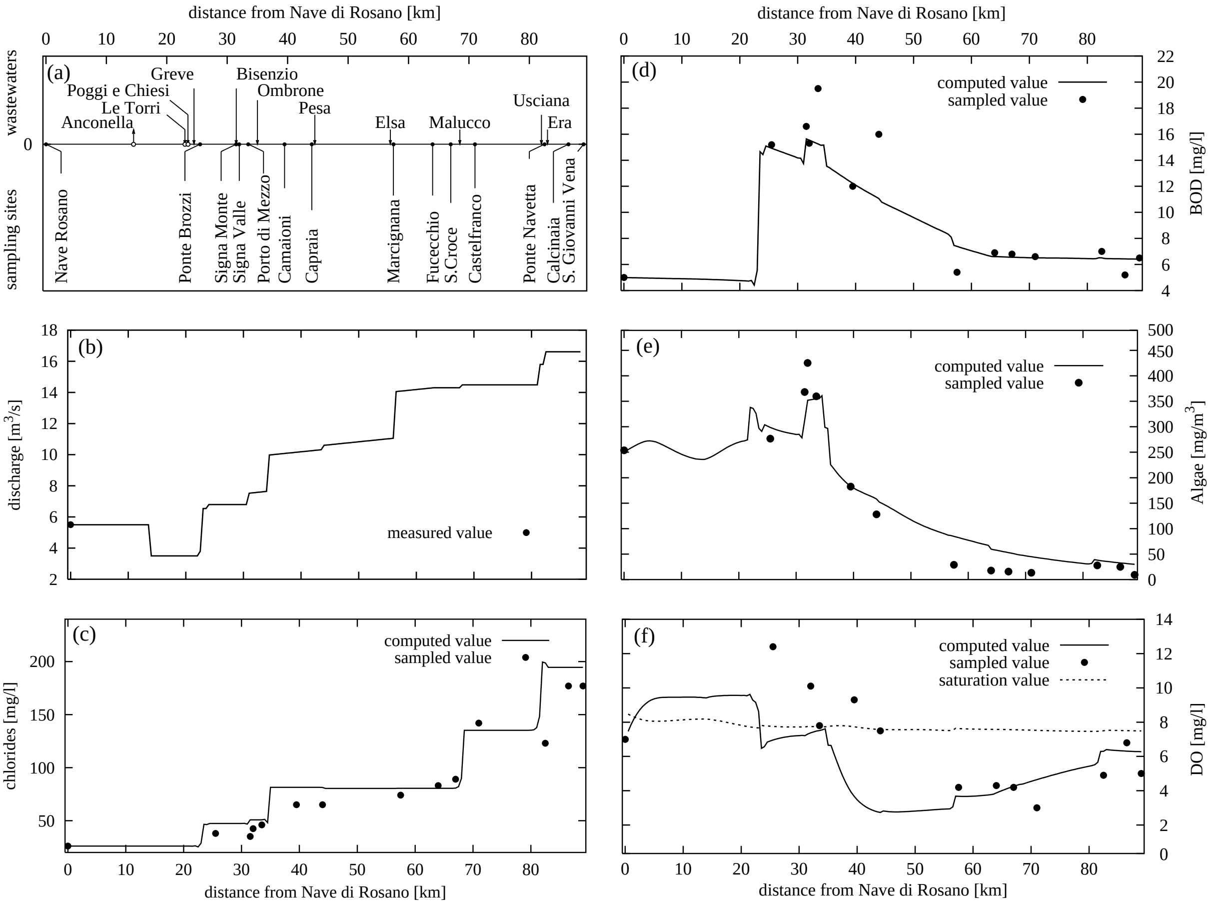

Fig. 2. Modeling of water quality in the Arno: (a) Map of river Arno from Nave di Rosano to S. Giovanni alla Vena: Tributaries, wastewaters and uptakes are indicated with arrows in the upper part of the figure; measuring points are below. (b) Discharge variation along the system; (c) Chlorides concentration; (d) BOD concentration; (e) Algae concentration; (f) DO concentration. Transit time is about 36 h from Nave di Rosano to S. Giovanni alla Vena. Experimental data (points) were collected on July 1996, 1st and 2nd.

along the river. Eight main tributaries (Greve, Bisenzio, Ombrone, Pesa, Elsa, Malucco, Usciana and Era) and two main wastewaters (Le Torri and Poggi e Chiesi), indicated in bold in Table 1, contribute to river flow rate. A withdrawal of water at Anconella is also considered, since it contributes significantly to flow rate reduction, especially during the low-flow period. Data were recorded at all locations shown in Fig. 2(a) for DO level, crucial for aquatic life, chlorides, leather, textile and paper industries waste products, biochemical oxygen demand (BOD) and algae. Measuring locations often correspond to a bridge: this was a bonus, since it was possible to sample the water quality in the middle of the river, where the mixing is higher. The downside of this choice is that DO measurements can be overestimated because of the surface renewal induced by the pillars of the bridge. Groundwater river recharge ($q = 0.0375\,\mathrm{m^3/s\,km}$), which is a significant contribution to the river flow rate during summer, was estimated from the July 1995 campaign and was considered for the portion of the river from 33 to 63 km.

2.2. Transport model

The model is based on a set of partial differential equations—mass, energy and momentum transfer equations—for a non-steady, one-dimensional system (see Table 2). Species transformations and reaction rates are the same as those used in QUAL2E [10]. Equations were written and solved for the computational representation of the river shown in Fig. 2(a), divided into 198 cells of length 500 m. Groups of cells (from 1 to 70, and from 71 to 198) are characterized by the same slope of the bottom, whereas a single averaged cross-section profile is assumed for the entire reach. Eq. (1) is used to model concentration for chlorides, BOD, DO and algae. The

Table 1
Discharge and water quality data collected for river Arno from Nave di Rosano to Ponte S. Giovanni during July 1996, 1st and 2nd. Locations in bold indicate wastewaters and tributaries, for which measurements refer to incoming discharge

Location	Discharge (m^3/s)	Chlorides (mg/l)	DO (mg/l)	BOD (mg/l)	Algae (mg/m^3)	Temperature (°C)	Day —	Time —
Nave di Rosano	5.5	26.0	7.0	5.0	250.0	23.1	01/07	9.00
Anconella[a]	−2.0	—	—	—	—	—	01/07	9.00
Le Torri	+0.30	92.0	2.1	(32.0)[b]	250.0	—	01/07	9.10
Poggi e Chiesi	+2.75	80.0	2.1	(32.0)[b]	250.0	—	01/07	9.50
Greve	+0.25	69.0	11.0	32.0	672.0	26.3	01/07	11.00
Ponte Brozzi	—	38.0	12.4	15.2	276.0	25.0	01/07	11.14
Signa monte	—	35.0	14.7	16.6	368.0	25.0	01/07	15.25
Bisenzio	+0.73	89.0	8.5	33.0	631.0	26.0	01/07	15.35
Signa valle	—	44.0	10.0	15.3	420.0	24.0	01/07	15.37
Porto di Mezzo	—	46.0	7.8	19.5	359.0	23.8	01/07	16.10
Ombrone	+2.32	200.0	2.8	8.0	76.0	26.9	01/07	17.14
Camaioni	—	65.0	9.3	11.5	182.0	23.8	01/07	20.00
Capraia	—	65.0	7.5	16.0	127.0	23.9	01/07	22.40
Pesa	+0.27	39.0	8.1	3.5	2.0	24.8	01/07	22.45
Marcignana	—	74.0	4.2	5.4	29.0	24.0	02/07	5.48
Elsa	+2.98	81.0	7.2	4.4	90.0	23.0	02/07	5.55
Fucecchio	—	83.0	4.3	6.9	17.0	23.5	02/07	7.32
S. Croce	—	89.0	4.2	6.8	15.0	24.0	02/07	8.41
Malucco	+0.19	4290.0	1.0	(6.7)[b]	0	30.5	02/07	9.33
Castelfranco	—	142.0	3.0	6.6	13.0	25.0	02/07	10.13
Usciana	+1.31	957.0	15.8	7.6	158.0	26.5	02/07	14.21
Ponte alla Navetta	—	123.0	4.8	7.0	27.0	27.0	02/07	14.24
Era	+0.81	89.0	9.4	5.4	25.0	20.5	02/07	14.55
Calcinaia	—	177.0	6.8	5.2	25.0	27.0	02/07	15.45
Ponte S. Giovanni	—	177.0	5.0	6.5	9.0	25.0	02/07	18.06

[a] Water quality at withdrawal is that of the river Arno.

[b] Estimated from equivalent inhabitants assuming BOD load equal to 25 g/eq. in. day [12] and number of equivalent inhabitants equal to 33,000, 304,000 and 4400 for Le Torri, Poggi e Chiesi and Malucco, respectively [9].

Table 2
Equations used by the model: conservation of mass species (1), species dispersion coefficient (2), conservation of energy (3), conservation of mass (4) and momentum (5)

Mass transport for species	$\frac{\partial A(h)C}{\partial t}=-\frac{\partial}{\partial x}[QC]+\frac{\partial}{\partial x}\left[DA(h)\frac{\partial C}{\partial x}\right]+A(h)\frac{\mathrm{d}C}{\mathrm{d}t}$	(1)
Dispersion coefficient [10]	$D=3.82knuh^{5/6}$	(2)
Energy equation	$\frac{\partial T}{\partial t}=-\frac{1}{A(h)}\frac{\partial}{\partial x}[QT]+\frac{1}{A(h)}\frac{\partial}{\partial x}\left[DA(h)\frac{\partial T}{\partial x}\right]+\frac{H_N}{\rho_w cd}$	(3)
Mass transport	$W(h)\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=0$	(4)
Momentum transport	$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left[\frac{Q^2}{A(h)}\right]+gA(h)\frac{\partial h}{\partial x}-gA(h)S_0+g\frac{n^2\lvert Q\rvert Q}{R(h)^{4/3}A(h)}=0$	(5)

rate of generation/consumption per unit volume $\mathrm{d}C/\mathrm{d}t$, was written ad hoc for each species, assuming first order kinetics, as reported in Table 3. Chlorides are conservative species, thus $\mathrm{d}C/\mathrm{d}t = 0$. Values and correlations for kinetic constants used in this work are shown in Table 4.

We solved first the hydraulic problem (Eqs. (4) and (5)), and then the energy equation (Eq. (3)) from which the temperature profile was obtained. Finally, we solved Eq. (1), written for each of the simulated pollutants, considering the effect of temperature on reaction rates. We integrated the finite-difference approximations of the differential equations using a two-point, implicit scheme for Eqs. (4) and (5) and a three-point implicit scheme—Crank–Nicolson scheme—for the ADRE (Eqs. (1) and (3)). Accuracy and stability of the numerical schemes were considered to choose the grid parameters (Δx and Δt) [11].

3. Water quality in the river Arno: the starting scenario

We used the flow rate at Nave di Rosano, the discharges from wastewaters and tributaries (see Table 1), and a stage discharge relationship at S. Giovanni alla Vena to solve Eqs. (4) and (5). Fig. 2(b) shows the calculated flow rate along the river. Since additional hydraulic data collected along the river were not available, we tested the hydraulics calculated by the model indirectly from pollutant transport data. We used species concentration at Nave di Rosano as inlet boundary, species concentration measured in the tributaries and in the wastewaters as boundary conditions and a Dirichlet condition at S. Giovanni alla Vena.

Fig. 2(c) shows the concentration calculated for chlorides. Chlorides entering from Ombrone, Malucco and Usciana increase the concentration along the river. Because of industrial settlements (paper, textile and leather industries), chlorides mass fluxes of the three tributaries are about 3, 6 and 9 times the mass flux at Nave di Rosano, respectively. Moreover, the closure of the chloride balance confirms the value for the river recharge by groundwater used for July 1996.

As shown in Fig. 2(d), in the upper part of the river—up to 22 km from Nave di Rosano—BOD concentration is uniform and equal to 5 mg/l. BOD increases steeply downstream of 22 km (wastewaters of Le Torri and Poggi e Chiesi), where the untreated sewage from Firenze joins the Arno. Downstream of the sewages, BOD decreases for progressive oxidation of the organic content. The organic content oxidation rate decreases downstream. The agreement with the experimental data is good, except for the values calculated for Porto di Mezzo, where large measured BOD gradients may be caused by a sharp left bend, and Capraia where, in summer time, the river is divided by a sand island which causes incomplete mixing.

Algae concentration (see Fig. 2(e)) decreases from Nave di Rosano to S. Giovanni alla Vena, with a local peak downstream of Bisenzio, due to the high inflow algae concentration.

Finally, Fig. 2(f) shows the variations calculated for DO concentration from the balance among BOD oxidation, algae dynamics and atmospheric reaeration (see Table 3), with the DO saturation value shown as a dotted line. Interestingly, the DO profile is very different upstream of and downstream of 35 km from Nave di Rosano, where there is the change in the bottom slope of the river. In the upper part of the river, the value of DO is around saturation. This indicates that reaeration

Table 3
Rate of generation/consumption for BOD, algae and DO

BOD	L	$\frac{\mathrm{d}L}{\mathrm{d}t} = -k_1 L$
Oxygen	O	$\frac{\mathrm{d}O}{\mathrm{d}t} = k_2(O^* - O) + (\alpha_3\mu - \alpha_4\rho)A_c - k_1 L$
Algae	A_c	$\frac{\mathrm{d}A_c}{\mathrm{d}t} = \mu A_c - \rho A_c - \frac{\sigma}{h}A_c$

*Superscript indicates concentration at saturation [10].

Table 4
Correlations and values of calibration parameters for model application to river Arno [9] with range from the literature [10]

Parameter	Correlation	
Reaeration coefficient, k_2 (day^{-1})	$k_2 = (D_m u)^{0.5}/h^{1.5}$ [13]	
Parameter	Value	Range of Literature [10]
Rate of degradation for BOD, k_1 (day^{-1})	0.16–0.01	[0.05 : 3.0]
Settling rate for algae, σ (m/day)	0.1	[0.0 : 17.0]
Oxygen production by algae, α_3 (mg O_2/mg algae)	1.8	[1.4 : 1.8]
Oxygen uptake by algae, α_4 (mg O_2/mg algae)	1.6	[1.6 : 2.3]
Algae max growth rate, μ (day^{-1})	2.0	[1.0 : 3.0]
Algae respiration rate, ρ (day^{-1})	0.4	[0.05 : 0.5]

mechanisms are very effective (the reaeration rate ranges from 5 to 7.5 day^{-1}) and DO production by algae is also significant. DO remains around saturation even after 22 km, where wastewaters of Le Torri and Poggi e Chiesi join the river Arno, adding high BOD and low DO water. Up to this point, the efficiency of reaeration seems to balance BOD degradation. Downstream of 35 km, the DO profile exhibits a sag, corresponding to a sharp decrease of the reaeration coefficient down to 1.5–1 day^{-1}, comparable to the BOD degradation rate. Predicted DO values are lower than those measured at Ponte Brozzi, Signa Monte, and Camaioni, corresponding to bridges, which increase the surface renewal, and at Porto di Mezzo, characterized by the sharp bend. However, experimental values of DO are above saturation, but sampling at these locations was made from 11.00 in the morning (Ponte Brozzi) to 16.10 (Porto di Mezzo), as from Table 1, when photosynthetic activity of algae may be important for DO increase.

Experimental data and simulations show that pollution in the river Arno is due to (i) growing concentration of chlorides along the course and (ii) high BOD load, which determines the decrease in DO in the lower part of the river. As observed, water quality conditions become critical for DO from 35 to 60 km downstream of Nave di Rosano, where DO concentration falls from 7 to about 3 mg/l.

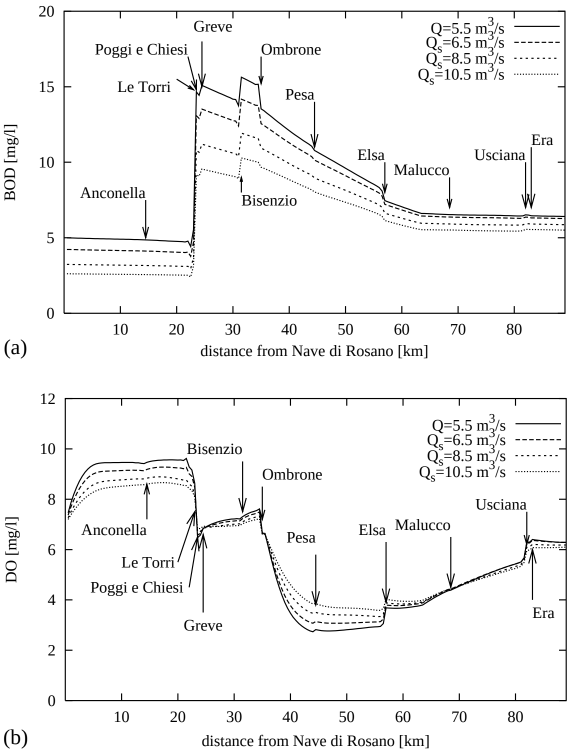

Fig. 3. Effect of different flow rates: (a) BOD concentration and (b) DO concentration along the course.

4. Evaluation and discussion of strategies for DO control

4.1. Reservoir management

Since the capacity of the river to degrade BOD and pollutants changes with the flow, we evaluated the effects produced on DO concentration for increased river flow, achieved by regulating the dam of Levane, 43 km upstream of Nave di Rosano. We considered flow rate variations equal to 1, 3 and 5 m^3/s that, from a previous work [4], were found to be minimum, average and maximum flow rate variations produced by dam release when river flow is the reference flow rate of about 5 m^3/s. We set inlet conditions for the increased flow rate using (i) the same concentration measured during the experimental campaign for DO, given the efficiency of reaeration mechanism and photosynthetic activity in the upper part of the river; (ii) the same load from waste for BOD, since BOD is due to sources independent of the river. Fig. 3(a) and (b) shows the variations of BOD concentration due to different reservoir management and the benefit produced in DO concentration by increased flow rate and BOD dilution. Through the increase of the water level and, consequently a reduction of the reaeration coefficient (see Table 4), the increase of the flow rate causes a reduction of DO concentration in the upper part of the river. In the lower part of the river, where BOD degradation produces the DO profile sag, DO is increased. DO concentration at the point of minimum rises up to 3.5 mg/l for a flow rate equal to 10.5 m^3/s while the minimum location moves downstream.

We also evaluated the effect of modulating the flow rate through time. Proper management of the dam at Levane can produce various hydraulic transients and improving the DO level by selecting a best schedule for water release could be an interesting possibility for water quality control. We simulated the increase of the reference flow rate (5.5 m^3/s) as produced by (i) a uniform dam release (+3 m^3/s) or (ii) a 24-h periodic sinusoidal release with the same mean value, and the same overall amount of water added during the day. Fig. 4 shows discharge and DO concentration time variations for two locations in the region of low dissolved oxygen (45 and 55 km, respectively). Lines with and without symbols represent daily DO variations due to constant flow rate and modulated flow rate, respectively. Variations of about 8% in the value of DO are produced locally by modulation. However, during the day, an increase or decrease in DO concentration is produced, depending on the location and thus on the phase difference between hydraulic perturbation and

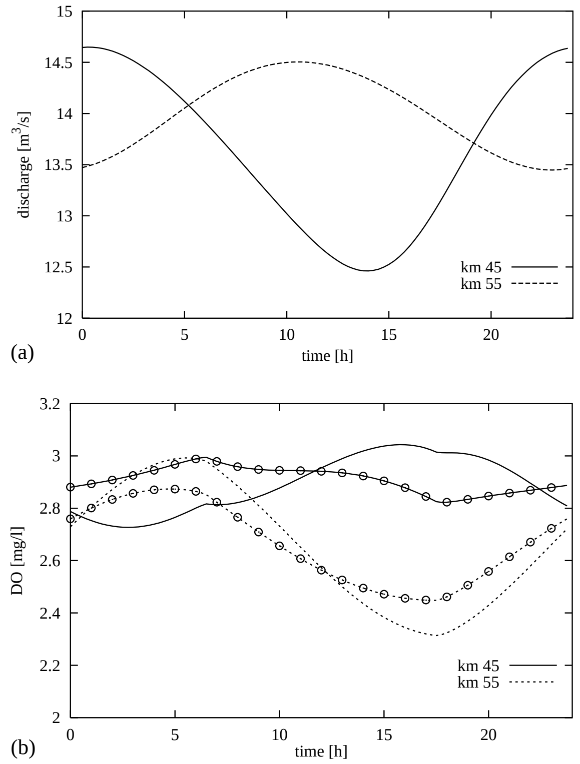

Fig. 4. Effects of reservoir management on water quality in river Arno. Temporal variation of discharge (a), and DO concentration (b) for two different locations along the course. Curves with points are variation of DO without flow rate modulation.

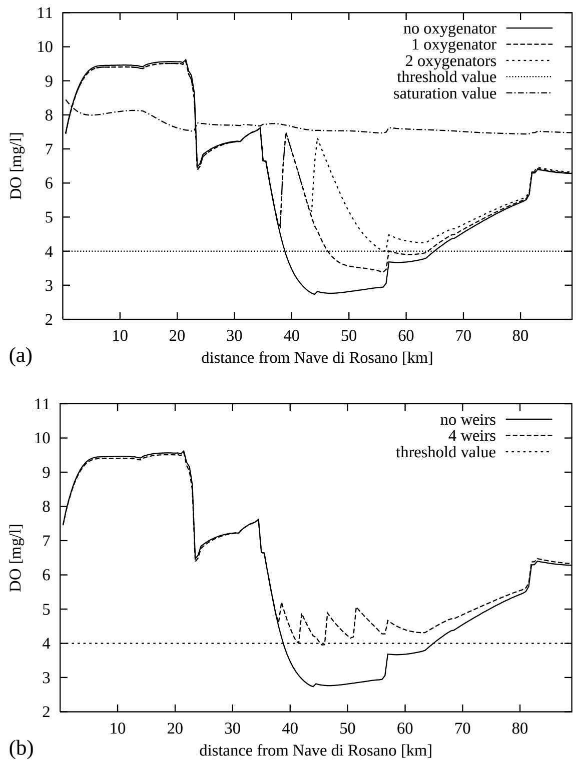

Fig. 5. Effect of local devices on DO concentration: (a) forced oxygenation, (b) natural oxygenation by weirs. Four weirs located at 39, 42, 46 and 52 km allow to maintain DO level above 4 mg/l.

diurnal cycle. Modulation produces DO reduction from 0 to 11 h at 45 km and DO increase at 55 km, respectively. The opposite is true for the rest of the day.

4.2. Local devices and DO concentration

We evaluated the effects of oxygenators along the river—more expensive, and of building of weirs – less expensive. The effect of oxygenators was simulated by assuming that the DO can increase up to saturation, and we evaluated the oxygen feed from local flow rate and oxygen deficit. Fig. 5(a) shows the DO profile along the river without oxygenators, with one and two oxygenators placed at 39 and 44 km: they are able to avoid DO below 4 mg/l, required for fish survival.

Then, we considered the building of weirs along the course. Flow over a weir produces strong oxygenation through air entertainment. The amount of oxygen entering the stream can be calculated using empirical correlation, relating the variation in local DO deficit to the geometrical characteristics of the weir, the fraction of the flow over the weir, the height of the weir and the quality of the water [10]. Fig. 5(b) shows the effect of weirs. After several trials, we found that to maintain DO level above 4 mg/l, four weirs located as shown in Fig. 5(b) are necessary.

4.3. Tailoring of wastewater load

Since the assimilative capacity of the river depends on the flow rate, when the flow rate is reduced, wastewater discharge and concentration should be reduced accordingly to maintain the target level of water quality. An option is tuning allowances for sewage discharge during periods of low flow, possibly achieved by treatment plants performing a tunable depuration process, in which the selection of primary and secondary treatments allow to obtain the BOD removal or concentration reduction desired. The sewage system of Firenze, still under construction, should take advantage of these technologies. We evaluated the concentration of wastewaters and tributaries required upstream of the critical DO region to meet the threshold DO value. We fixed trial values of reduced concentration for BOD loads at

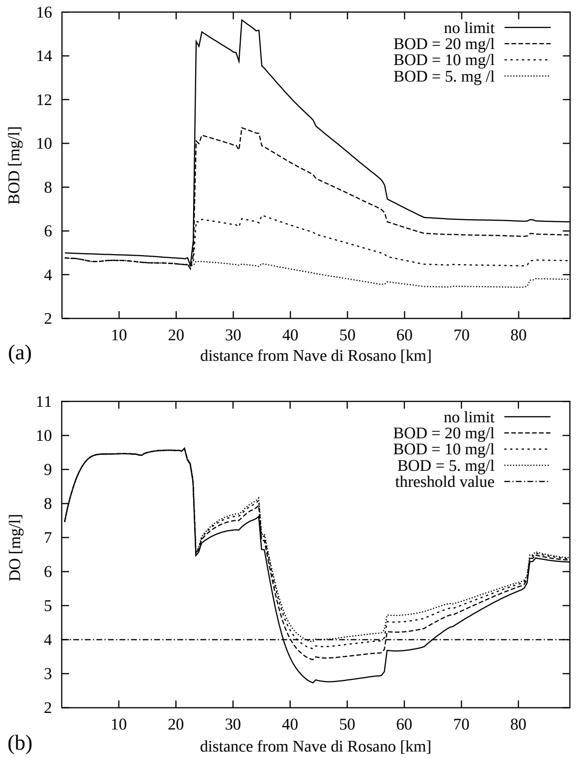

Fig. 6. Effect of wastewater BOD concentration on water quality: (a) BOD concentration and (b) DO concentration along the Arno for different BOD limits at point loads.

20, 10 and 5 mg/l, assuming a constant discharge into the river. Larger wastewaters BOD concentrations were reduced accordingly. It should be noted that reduction of concentration hypothesized for wastewaters is far below the legal limit for the concentration (40 mg/l) of wastewaters discharging in surface waters. Fig. 6(a) shows profiles of BOD obtained by the simulations, and Fig. 6(b) shows corresponding DO concentrations. Reducing the BOD load from the sewer system of Firenze onward improves the level of DO. However, to meet the DO threshold value of 4 mg/l, BOD concentration for wastewaters should be reduced down to 5 mg/l, for the hydraulic regime considered (5.5 m^3/s). At present, this is a rather stringent constraint for wastewater loads and makes a variable discharge permit program difficult to impose.

Acknowledgements

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