Evaluation of the Water Quality in the Guadarrama River at the Section of Las Rozas-Madrid, Spain

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Abstract

The variation of the water quality of the Guadarrama river and its tributaries in a section of Las Rozas-Madrid, Spain, was studied during the time period elapsed between January 2003 and January 2008. The parameter Water Quality Index (*WQI*) was used to determine the water quality based on the conventional parameters of pollution. It was found that the water quality index was slightly affected in the section evaluated. The value of the water quality index was in the range of 56-64, which corresponded to the classification of "good quality". It was determined that 64.3 % of the organic matter present in the river was removed in the section of Las Rozas-Madrid. The river acted as a plug flow reactor and a first-order kinetics governed the ultimate BOD_5 (BOD_U) decay. The value of the first-order constant demonstrated the river's high self-purification capacity. In addition, a high linear relationship between the *WQI* and the dissolved oxygen deficit (*D*) was found. Therefore, a quick determination of *WQI* may be carried out if the values of *D* are known. These are easily obtainable by field measurements.

Keywords: first-order kinetics; Guadarrama river; plug-flow; water quality index (WQI).

Introduction

The Guadarrama River is an important tributary of the Tajo River, being one of the most important rivers of the Autonomous Community of Madrid (Spain). It begins in the Madrid region and runs 131.8 km through the Madrid and Toledo provinces before flowing into the Tajo River. Figure 1 shows a map with the total course of the

Guadarrama river. The drainage area of the Guadarrama covers approximately 1,700 km^2, with almost 90 km^2 (7.4 km length) corresponding to the municipality of Las Rozas-Madrid (Spain). Upstream and before entering this municipality, the river receives the final effluent from the sewage wastewater treatment plant at Villalba located in the municipality of Torrelodones, as can be observed in Figure 1 map. In the area of Las Rozas-Madrid, the Guadarrama receives the influents of La Torre, La Virgen and Fuentecillas creeks. At the same time, La Torre creek has an influent called Motilona creek with a flow constituted by the final effluents of three sewage wastewater treatment plants.

The average flow of the Guadarrama river in the section corresponding to Las Rozas-Madrid was 1.54 m^3/s in the period from 2003-2008, with a maximum of 5.36 m^3/s in autumn and spring and a minimum of 0.49 m^3/s in winter and summer. The average width of the river is 7.1 m while the average depth is estimated at 0.5 m. The Las Rozas-Madrid municipality has a population of approximately 75,000 with around 80 % of the population connected to the sewage system. Part of the final effluents of the wastewater treatment plants are discharged into the influents previously mentioned.

The evaluation of water quality in different countries has become a critical issue in recent years due to the population increase and the growing demand for water (Prati et al., 1971; Mummé, 1979; Poch et al., 1986; Bhargava, 1985; Pesce and Wunderlin, 2000; Chang et al., 2001; Cox, 2003; Lopes et al., 2004; Zheng et al., 2004; Bellos and Sawidis, 2005; Liu et al., 2005; Kachiashvili et al., 2006; Kowalkowski et al., 2006; Ocampo-Duque et al., 2006; Ouyang, et al., 2006; Absalon and Matysik, 2007; Beamonte et al., 2007; Even et al., 2007; Gui-zhen et al., 2007; Icaga, 2007; Lindenschmidt et al.; 2007; Naddeo et al., 2007; Paliwal et al., 2007; Sánchez et al., 2007). These authors have used different methods to facilitate the evaluation and classification of the quality of natural waters based on numerous parameters and to determine the influence of pollutants on the quality of river water. One of the most frequently used parameters worldwide is the Water Quality Index (*WQI*). This index has proved to be an acceptable instrument for transforming a large amount of data into a simple number that allows for the quality of a stream and its evolution in time or distance to be classified. The determination of *WQI* requires a normalization step where each parameter is transformed into a 0-100 scale, where 100 represents the maximum quality. The next step is to apply a weighting factor in accordance with the importance of the parameter (Bhargava, 1985; Nives, 1999; Pesce and Wunderlin, 2000; Chang et al., 2001; Ocampo-Duque et al., 2006; Gui-zhen et al., 2007; Sánchez et al., 2007). The dissolved oxygen (*DO*) and dissolved oxygen deficit (*D*) have been used in a numbers of cases to evaluate the water quality of different reservoirs and streams. They are influenced by parameters that at the same time determine the quality of the water such as biochemical oxygen demand, chemical oxygen demand, suspended and dissolved solids, nitrogen and phosphorus species, microalgae and heterotrophic bacteria, pH, electrical conductivity and temperature. An increase in the values of these parameters causes a decrease in *DO* and an increase in *D,* which in turn determines the decrease of *WQI*. On the other hand, the lower the concentration of BOD_5, COD, electrical conductivity, nitrogen and phosphorus compounds, dissolved and suspended solids, heterotrophic bacteria and microalgae, the more the water quality improves, increasing *DO* and decreasing the value of *D* (Prati et al., 1971; Cox, 2003). Therefore, *DO* and *D* have previously been used as a simple estimation of the quality of natural waters and the dynamics of pollution due to effluent disposal (Mummé, 1979; Bhargava, 1985; Poch et al., 1986; Ansa-Asare et al., 2000; Pesce and Wunderlin, 2000; Cox, 2003; Lopes et al., 2004; Liu et al., 2005; Icaga, 2007; Lindenschmidt et al.; 2007; Paliwal et al., 2007; Sánchez et al., 2007). In addition, the variation of the organic matter concentration in a section of a creek may be modelled following a first-order kinetics, according to a plug-flow system, as has been reported by several authors (Boyle and Scott, 1984; Poch et al., 1986; Van Orden and Uchrin, 1993; Campolo et al., 2002; Cox, 2003).

Based on the literature reviewed, the quality of the Guadarrama river water and its influents were studied and classified in accordance with the data obtained, using the integration parameter of quality *WQI*. The capacity of organic matter removal of the river in the section of Las Rozas-Madrid was also evaluated.

Materials and Methods

Description of the sampling points

Figure 2 shows the different locations of the sampling points of the Guadarrama river and its influents in Las Rozas-Madrid section.

Motilona creek

Motilona creek is a tributary of La Torre creek and at the same time is the final disposal watercourse of two sewage treatment plants serving a population of 1,210. The average flow of the creek downstream of the discharge of the sewage treatment plant effluents is estimated at 9 l/s. Five sampling points were selected from this creek: Motilona 1 (M 1), at the beginning of the creek, coinciding with the point of discharge of the sewage treatment plant "El Encinar de las Rozas" serving a population of 665 (1.5 l/s); Motilona 2 (M 2), 0.15 km downstream; Motilona 3 (M 3), 0.35 km downstream, corresponding with the point of discharge of the final effluents of the sewage treatment plant "Jardines del Cesar” serving a population of 550 (1.3 l/s); Motilona 4 (M 4), 1.35 km downstream and, finally, Motilona 5 (M 5), 2.00 km downstream and just before the mixing point with La Torre creek.

La Torre creek

La Torre creek is a tributary of the Guadarrama river. Four sampling points were selected from this creek: Torre 1 (T 1), at the beginning of the creek; Torre 2 (T 2), 1.90 km downstream, just before the mixing point with Motilona creek; Torre 3 (T 3), 2.54 km downstream and, finally, Torre 4 (T 4), 4.61 km downstream just before the mixing point with the Guadarrama river. In this case the average flow achieves a value of 37.3 l/s before the mixing point with the Guadarrama river.

La Virgen creek

La Virgen creek is an influent of the Guadarrama river located downstream from the discharge of La Torre creek. This creek receives the effluents of a sewage treatment plant serving a population of 3,500. The average flow of effluents achieves a value of 8.3 l/s while the average flow of the creek is 14.5 l/s. Three sampling points were selected in this case: Virgen 1 (V 1), at the beginning of the creek; Virgen 2 (V 2), 0.96 km downstream and, finally, Virgen 3 (V 3), 1.68 km downstream.

Fuentecillas creek

Fuentecillas creek is an influent of the Guadarrama river located downstream from La Virgen creek. This tributary receives the effluents of a sewage treatment plant serving a population of 650 with an average flow of 1.5 l/s. The average flow of the creek is 6.1 l/s. Three sampling points were selected in this case: Fuentecillas 1 (F 1), at the beginning, which coincided with the point of discharge of the sewage treatment plant disposal; Fuentecillas 2 (F 2), 0.67 km downstream and, finally, Fuentecillas 3 (F 3), 2.71 km downstream.

The Guadarrama river

Seven sampling points were selected from the Guadarrama river: Guadarrama 1 (G 1) located just at the inlet point of the municipality; Guadarrama 2 (G 2), 1.75 km downstream; Guadarrama 3 (G 3), 2.45 km downstream; Guadarrama 4 (G 4), 3.36 km downstream from the inlet point and further down from the mixing point with La Torre creek; Guadarrama 5 (G 5), 4.45 km downstream and after the mixing point with La Virgen creek; Guadarrama 6 (G 6), 6 km downstream and Guadarrama 7 (G 7), at the outlet point of the municipality, located 7.4 km downstream and after the mixing point with Fuentecillas creek.

Sampling procedure

The sampling period spread over a total period of five years from January 2003 to January 2008. The samples were taken once a week and after the determination of field parameters they were transported to the laboratory and preserved at 4ºC.

Climate conditions

Table 1 shows the temperatures and rainfalls throughout the four seasons during the sampling period.

Field determinations and laboratory analyses

Field determinations of pH, electrical conductivity (K_E), temperature (TºC) and dissolved oxygen (*DO*) were carried out using portable equipment according to the Standard Methods for the Examination of Water and Wastewaters (APHA, 1999). The K_E, pH and *DO* were measured using "Hanna", "Crison" and "Inolab WTW" portable equipment, respectively. Laboratory analyses were carried out for the determinations of total suspended solids (TSS), ammonia (Amm.), nitrite (NO_2^-), nitrate (NO_3^-), total phosphorus (P), chemical oxygen demand (COD), and biochemical oxygen demand (BOD_5). These analyses were also performed using the methodology recommended by the Standard Methods (APHA, 1999).

Determination of the *WQI*

For the determination of the water quality index (*WQI*) of the different creeks studied, the following empirical equation was used (Pesce and Wunderling, 2000):

$$WQI = [(\Sigma_i P_i C_i)/(\Sigma_i P_i)] \qquad (1)$$

where C_i is the normalized value of the parameters (as far as quality is concerned) which increases as the parameter approaches to the optimum and P_i is the relative weight associated to each parameter, giving an index of the relative importance in the water quality standards (EU, 1975; Pesce and Wunderlin, 2000; Sánchez et al., 2007). This is a simple equation to determine the *WQI* that may be used by laboratories for water quality studies at town or regional level. Table 2 shows the values of C_i and P_i of equation (1).

Results and Discussion

Motilona creek

Table 3 shows the values of the parameters evaluated for Motilona creek. The pH values remained slightly higher than 7.0 in all sampling points except at M 2. Electrical conductivity decreased from M 1 to M 4 but increased at M 5 to the highest value, probably due to the solubilization of particulate solids. Maximum values of nitrites and nitrates were observed at M 3 and M 4. In the case of ammonia and phosphorus, maximum values were observed at M 1, M 4 and M 5 where maximum values of electrical conductivity were observed. The minimum concentration of dissolved oxygen corresponded with the highest values of electrical conductivity and concentrations of ammonia, phosphorus, COD, and BOD_5. With the values of dissolved oxygen and temperature, the values of oxygen deficit (*D*) were determined from the difference between the saturation concentrations at a given temperature and the actual *DO* concentrations at the same temperature (Sánchez et al., 2007).

The values of COD, BOD_5, *DO*, *D* and the *WQI* for Motilona creek are plotted in Figure 3. Dissolved oxygen values were at a minimum at the point of discharge of the effluents of the sewage treatment plants (M 1 and M 3). The minimum value of *WQI* corresponded with the minimum *DO* and maximum COD, BOD_5 and *D* at M 4 (1.35 km downstream). Therefore, critical oxygen deficit (D_C) may be located 1.35 km downstream.

La Torre creek

Table 4 shows the values of the parameters evaluated along La Torre creek. The pH remained at values slightly higher than 7.0. The electrical conductivity at T 1 was considerably lower than that obtained at T 2. The value of the electrical conductivity at the mixing point with Motilona creek was 0.68, it decreased to 0.61 at T 3 and increased again at T 4, as a consequence of the organic matter mineralization. The concentration of suspended solids decreased from T 1 to T 2 due to the sedimentation of suspended particles and a partial solubilization causing an increase in the concentration of dissolved solids which determined the increase in the electrical conductivity. Nitrite concentration remained practically constant while nitrates decreased from T 1 to T 2 increasing from T 2 to T 4 due to the oxidation reaction. The concentration of ammonia increased from T 1 to T 2 probably due to the degradation of organic nitrogen to ammonia and decreased downstream. The concentration of phosphorus increased from T 1 to T 3 decreasing further on.

Figure 4 shows the values of COD, BOD_5, *DO*, *D* and the *WQI*. The profiles obtained show a progressive decrease of COD downstream. BOD_5 increased 1.9 km downstream, whereas an initial decrease was observed downstream at the mixing point with Motilona creek, with a further increase 4.61 km just before the discharge into the Guadarrama river. At the same time, the *DO* decreased initially as a consequence of the decomposition of organic matter achieving a minimum value at 1.9 km, then increased at 2.54 km, and finally decreased again downstream due to the influence of the discharge of Motilona creek. As can be seen, *D* showed a maximum value 1.9 km from the initial point and increased again after the incorporation of Motilona creek. In addition, the *WQI* was in the range of 39-44 showing that the water of La Torre creek may be classified as "bad quality". Therefore, the self-purification capacity of La Torre creek was not good enough to allow for the discharge of three wastewater treatment plant effluents.

La Virgen creek

Table 5 shows the parameters evaluated along La Virgen creek. The pH remained at values slightly higher than 7.0. Electrical conductivity was practically constant with values in the range of 0.7-0.8 mS/cm, showing a relatively high concentration of dissolved matter. The concentration of suspended solids decreased along the creek, probably due to the sedimentation of suspended particles and the partial solubilization increasing the concentration of dissolved solids and the electrical conductivity. Nitrite concentration remained practically constant while nitrates increased from V 1 to V 3 due to the oxidation reaction coinciding with the decrease in ammonia nitrogen concentration.

At the same time, phosphorus concentration increased downstream probably due to the decomposition of settled organic solids containing condensed phosphorus. The variation of the values of COD, BOD_5, *DO*, *D* and *WQI* according to the distance along the creek is presented in Figure 5. COD and BOD_5 had slight variations along the creek. The *DO* concentration was at a minimum 1.9 km downstream coinciding with the maximum oxygen deficit. Therefore, the critical distance corresponded to 1.9 km from the beginning. In addition, the *WQI* was in the range of 50-60, which is better than the other creeks evaluated.

Fuentecillas creek

Table 6 shows values of the parameters along Fuentecillas creek. The pH remained at around 7.0. The electrical conductivity was practically constant with values in the range of 0.7-0.8 mS/cm. The concentration of suspended solids was relatively low, increasing just before the discharge into the Guadarrama river. Nitrates increased from F 1 to F 2 due to the oxidation reaction of ammonia and decreased downstream at F 3 probably due to the activity of autotrophic organisms. In addition, the concentration of phosphorus decreased progressively downstream from the beginning of the creek which also coincided with the discharge of the effluent from a sewage treatment plant. The variation of the values of COD, BOD_5, *DO*, *D* and *WQI* is illustrated in Figure 6. This Figure shows a considerable decrease of the COD and BOD_5 according to their location along the creek. The concentration of dissolved oxygen increased while the oxygen deficit decreased along the creek.. The *WQI* increased from around 50 units to nearly 70 at the point of discharge of the Guadarrama river.

Guadarrama river

The values of pH downstream remained between neutral and slightly acidic. The values of electrical conductivity remained around 0.4 mS/cm, which corresponded to values commonly found in natural waters. A considerable increase of suspended solids was observed from G 1 to G 2 but, decreased to values in the range of 8-21 mg/l downstream. Nitrite concentration remained practically constant. Nitrate concentration was relatively high at G 1 as a consequence of the disposal of effluents from the Villalba sewage treatment plant located upstream, decreasing along the river but it was 11.0 mg/l at the point G 7, a value that is not acceptable for natural waters. Ammonia concentration decreased slightly downstream showing the lowest value at point G 7. Phosphorus concentration decreased slightly from G 1 to G 5 but increased at G 6, decreasing finally at G 7. The profiles of COD, BOD_5, *WQI*, *DO* and *D* are given in Figure 7. This Figure shows that COD had slight variations and BOD_5 decreased slightly along the river in spite of the discharge of three creeks at different points with different concentrations of organic matter.

Dissolved oxygen concentration and oxygen deficit achieved maximum and minimum values respectively at 2.45 km from the inlet point (G 3). Therefore, the critical oxygen deficit (D_C) may be considered at this distance. The concentration of dissolved oxygen decreased by around 1.5 mg/l when comparing G 1 and G 7, although the concentration of dissolved oxygen along the river was high enough to maintain ecological equilibrium. The *WQI* along the river was in the range of 60-70 units, acceptable values for natural waters. These *WQI* values were as high as those found in reservoir waters belonging to "El Hondo" natural park located in the east of Spain (province of Alicante) (Colmenarejo et al., 2007).

Material balance

A material balance of the Guadarrama river in the section of Las Rozas-Madrid was carried out based on ultimate biological oxygen demand (BOD_U) and can be established as follows:

$$L_{G\,1} + L_{T\,4} + L_{V\,3} + L_{F\,3} - L_{G\,7} = L_R \qquad (2)$$

where $L_{G\,1}$ is the organic load (kg BOD_U/d) at the starting or inlet point (G 1), $L_{T\,4}$ is the inlet organic load (kg BOD_U/d) at the point of discharge of La Torre creek to Guadarrama river, $L_{V\,3}$ is the inlet organic load (kg BOD_U/d) at the point of discharge of La Virgen creek to Guadarrama river with, $L_{F\,3}$ is the inlet organic load (kg BOD_U/d) at the point of discharge of Fuentecillas creek to Guadarrama river, $L_{G\,7}$ is the outlet organic load (kg BOD_U/d) at Las Rozas-Madrid (G 7), and L_R is the organic load (kg BOD_U/d) removed by the Guadarama river in the section of Las Rozas- Madrid. The organic load is given by the expression: $L = Q$ (BOD_U), where Q is the flow (m^3/d) and BOD_U is the ultimate BOD (in kg/m^3) given by the expression:

$$BOD_U = BOD_5/[1-e^{-k\,t}] \qquad (3)$$

where k was assumed to be 0.3 d^{-1} according to the temperature (20 °C) and the characteristics of the organic matter in the river (Zanoni, 1967; Adrian and Sanders, 1998) and t = 5 d

L_R is the organic load removed and is given by the expression:

$$L_R = Q[C_0 - C_E] \qquad (4)$$

where Q is the average flow of the river (m^3/d), C_0 is the BOD_U at the inlet or initial point of the river and C_E is the BOD_U at the outlet of Las Rozas-Madrid. A summary of the average values of the mentioned organic loads are given in Table 8. The results summarized in Table 8 show that 86% of the biodegradable organic matter comes from the outlet of the section evaluated. The principal contribution to the river pollution in the section of Las Rozas-Madrid originates in La Torre creek but this pollution represents only 11% of the total pollution of the river. In addition, in the section of Las Rozas-Madrid, river pollution decreased by 64.3%. At the same time, the value of C_E depends on the BOD_U at the inlet (C_0) and the retention time in the section can be considered by the following equation, which is formulated taking into account that the river behaves as a plug-flow reactor (Boyle and Scott, 1984; Poch et al., 1986; Van Orden and Uchrin, 1993; Campolo et al., 2002; Cox, 2003):

$$C = C_0 e^{-K\,t} \qquad (5)$$

where K is the constant of the first-order reaction (h^{-1}), t is the time (h) to reach a given sampling point and is the quotient between the distance (km) of the given sampling point (d) and the average river velocity (v) in km/h, and C is the BOD_U at the corresponding time obtained (kg/m^3). The value of C at the outlet point is equivalent to C_E.

In order to demonstrate the feasibility of the application equation (5) to the experimental results obtained, the naeperian logarithm of the quotient C/C_0 was plotted versus the time. As can be seen in Figure 8 a straight line was obtained, which demonstrated that a first-order kinetics and plug-flow system can be applied and considered for explaining the results obtained. The determination coefficient R^2 was found to be 0.98 with an error probability $P \leq 5\%$. The value of the constant *K* in this hypothetical plug-flow reactor is equivalent to the constant of deoxygenation and was found to be $0.10 \pm 0.01\ h^{-1}$. The value of *K* obtained is in the range of the values compiled in the literature reported (Boyle and Scott, 1984; Van Orden and Uchrin, 1993; Stefan and Fang, 1994; Campolo et al., 2002). Therefore, in the section of Las Rozas-Madrid the BOD_U decay occurred according to a first-order kinetics in a plug-flow system.

Correlation between *D* and *WQI*

From the results obtained in the different sampling points monitored, a high dependence of the *WQI* with respect to the oxygen deficit (*D*) was observed. As was previously mentioned, the concentration of dissolved oxygen in a watershed depends on the BOD_5, COD, dissolved and suspended solids, electrical conductivity, nitrogenous and phosphorous compounds, microorganisms and temperature of the water (Mummé, 1979; Bhargava, 1985; Poch et al., 1986; Ansa-Asare et al., 2000; Pesce and Wunderlin, 2000; Cox, 2003; Lopes et al., 2004; Liu et al., 2005; Icaga, 2007; Lindenschmidt et al.; 2007; Paliwal et al., 2007; Sánchez et al., 2007). In addition, given that the *WQI* is an integration value of the above mentioned parameters, a correlation between oxygen deficit and water quality index should exist. This correlation may be a useful instrument for a fast estimation of the water quality of the creeks studied based on a simple determination of the temperature and the dissolved oxygen. To demonstrate this hypothesis the values of *D* for the creeks studied were plotted versus the values of *WQI* for all sampling points monitored. Figure 9 shows that a straight line correlates the parameters *D* and *WQI* by with a determination coefficient $R^2 = 0.91$ and a margin of error of $P \leq 10$ %. Therefore, the *WQI* may be estimated as a function of *D* by the following linear equation:

$$WQI = -4.9\, D + 79.0 \qquad (6)$$

Dissolved oxygen and oxygen deficit are parameters frequently used to evaluate the water quality of different reservoirs and watersheds. These parameters are strongly influenced by a combination of physical, chemical and biological characteristics of streams of oxygen demanding substances, including algal biomass, dissolved organic matter, ammonia, volatile suspended solids, and sediment oxygen demand (Cox, 2003). Williams et al. (2000) studied the water quality variation in three rivers of the United Kingdom. The authors also established an empirical equation between the oxygen deficit, the average photosynthesis rate and the average respiration rate. The use of dissolved oxygen content as an index of water quality was also used to estimate the effect of industrial and municipal effluents on the waters of San Vicente Bay, Chile (Rudolf et al., 2002). The results suggested that the oxygen depletion was a representative parameter for establishing a relative scale of water quality in these waters.

Conclusions

The monitoring of the Guadarrama river and its tributaries over a 5 year period has demonstrated the need to improve the efficiencies of the sewage wastewater treatment plants that serve the population of Las Rozas-Madrid. The greatest source of pollution of the Guadarrama river is La Torre creek, due to the discharge of insufficiently treated wastewater in Motilona creek. The other tributaries of the Guadarrama river do not affect the quality of the river water.

The Guadarrama river was found to have a great capacity for overcoming the discharge of pollutants in the section of Las Rozas. Otherwise, the pollutant removal achieved a value of 64.3 %. Therefore, the river travels through the section of Las Rozas-Madrid with a considerably lower level of pollution than at the inlet. It was found that organic pollution decay follows a first-order kinetics according to a plug-flow system.

A strong correlation between the dissolved oxygen deficit (*D*) and the *WQI* was found. This correlation is a useful instrument for evaluating the state of the river and tributary waters by a simple monitoring of *DO* and temperature. However, the application of this correlation to other streams and under other climatic conditions must be individually demonstrated.

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Table 1. Temperatures and rainfalls during the period evaluated (January 2003-January 2008)

Season	Temperature variation (ºC)			Rainfall (mm)	
	$T_{Min.}$	$T_{Med.}$	$T_{Max.}$	Monthly	Total
Winter	1.3 ± 3.6	7.7 ± 3.3	11.9 ± 3.9	18.5 ± 25.1	75.4 ± 40.8
Spring	11.3 ± 0.7	16.9 ± 5.0	22.2 ± 6.8	36.0 ± 32.5	93.8 ± 80.9
Summer	18.2 ± 3.0	27.0 ± 3.3	31.4 ± 4.1	5.5 ± 7.3	13.9 ± 12.9
Autumn	7.4 ± 5.2	13.0 ± 3.4	17.2 ± 6.0	48.8 ± 36.3	128.4 ± 60.5

Table 2. Values of C_i and P_i for the most important parameters used for the determination of the Water Quality Index (*WQI*).*

Parameter	P_i	C_i										
		100	90	80	70	60	50	40	30	20	10	0
pH	1	7	7-8	7-8,5	7-9	6,5-7	6-9,5	5-10	4-11	3-12	2-13	1-14
K_E	2	<0,75	<1,00	<1,25	<1,50	<2,00	<2,50	<3,00	<5,00	<8,00	<12,00	>12,00
TSS	4	<20	<40	<60	<80	<100	<120	<160	<240	<320	<400	>400
NO_2^-	2	< 0,005	<0,01	<0,03	<0,05	<0,10	<0,15	<0,20	<0,25	<0,50	<1,00	> 1,00
NO_3^-	2	< 0,5	<2,0	<4,0	<6,0	<8,0	<10,0	<15,0	<20,0	<50,0	<100,0	> 100,0
Amm.	3	< 0,01	<0,05	<0,10	<0,20	<0,30	<0,40	<0,50	<0,75	<1,00	<1,25	>1,25
P	1	< 0,2	<1,6	<3,2	<6,4	<9,6	<16,0	<32,0	<64,0	<96,0	<160,0	> 160,0
COD	3	< 5	<10	<20	<30	<40	<50	<60	<80	<100	<150	> 150
BOD_5	3	< 0,5	<2,0	<3	<4	<5	<6	<8	<10	<12	<15	> 15
D O	4	≥ 7,5	>7,0	>6,5	>6,0	>5,0	>4,0	>3,5	>3,0	>2,0	>1,0	< 1,0
T°C	1	21/16	22/15	24/14	26/12	28/10	30/5	32/0	36/-2	40/-4	45/-6	>45/<-6

* The values of C_i, P_i and pH are dimensionless; the values of K_E, are given in mS/cm; the values of the rest of parameters are given in mg/l.

Table 3. Results obtained during the monitoring of Motilona Creek

M 1: Distance (km) = 0.00											
Parameter	pH	K_E mS/cm	S.S mg/l	Nitrites (mg/l)	Nitrates (mg/l	Ammonia (mg/l)	P (mg/l)	COD (mg/l)	BOD_5 (mg/l)	DO (mg/l)	T (ºC)
Mean	7.2	0.71	154	0.04	2.1	19.8	3.3	413.7	60.8	2.4	11.9
S D	0.2	0.05	141	0.03	0.9	12.2	2.8	241.8	45.3	1.4	5.4
Max.	7.5	0.79	398	0.08	3.2	37.1	5.3	715.3	105.9	4.0	19.7
Min.	7.0	0.65	35	0.02	1.0	2.8	1.4	131.6	8.4	0.3	6.0
M 2: Distance (km) = 0.15											
Mean	6.5	0.43	4.5	0.03	1.9	0.8	0.9	4.5	2.5	6.6	14.9
S D	0.3	0.05	0.8	0.02	1.8	0.3	0.5	5.4	2.1	0.7	5.1
Max.	6.3	0.47	5.3	0.05	4.2	1.3	1.4	11.4	3.4	7.5	18.3
Min.	6.9	0.38	3.7	0.02	0.7	0.7	0.5	2.5	0.8	6.1	4.1
M 3: Distance (km) = 0.35											
Mean	7.3	0.62	38	0.25	16	9.1	4.4	130.3	46.6	5.5	11.8
S D	0.3	0.14	44	0.35	22	8.4	4.6	99.5	42.2	2.7	4.9
Max.	7.7	0.82	135	1.04	68	25.4	10.3	322.6	128.5	12.0	19.2
Min.	7.0	0.38	5	0.00	1	1.4	0.2	23.4	9.4	2.5	3.7
M 4: Distance (km) = 1.35											
Mean	7.2	0.62	56	0.21	5.8	10.9	9.5	261.5	117.4	3.1	11.6
S D	0.3	0.12	47	0.10	2.0	3.2	6.1	100.6	59.8	1.5	7.4
Max.	7.5	0.80	102	0.37	7.2	13.2	13.9	310.5	172.5	5.5	18.9
Min.	7.0	0.56	8	0.18	3.3	6.8	1.9	115.6	53.6	2.7	4.1
M 5: Distance (km) = 2.00											
Mean	7.4	0.77	64	0.05	1.3	17.0	5.5	223.4	110.2	4.3	13.0
S D	0.2	0.05	74	0.04	0.4	12.7	5.2	221.5	159.5	2.1	4.7
Max.	7.6	0.82	213	0.10	1.7	32.2	10.9	620.5	350.2	6.5	19.1
Min.	7.1	0.70	12	0.00	0.9	1.1	0.6	21.4	15.4	1.2	6.4

Table 4. Results obtained during the monitoring of La Torre Creek.

T 1: Distance (km) = 0.00											
Parameter	pH	K_E mS/cm	S.S mg/l	Nitrites (mg/l)	Nitrates (mg/l	Ammonia (mg/l)	P (mg/l)	COD (mg/l)	BOD_5 (mg/l)	DO (mg/l)	T (ºC)
Mean	7.1	0.65	41	0.12	2.5	9.9	3.5	116.8	44.6	3.7	12.3
S D	0.2	0.15	35	0.15	2.0	8.4	2.8	65.1	22.7	2.6	4.5
Max.	7.4	0.89	119	0.38	5.9	21.5	8.4	243.4	80.1	7.5	19.7
Min.	6.7	0.37	2	0.02	0.6	1.0	0.4	42.2	17.5	0.6	5.1
T 2: Distance (km) = 1.90											
Mean	7.2	0.70	16	0.10	1.6	12.6	3.7	109.5	49.7	3.5	11.5
S D	0.2	0.09	9	0.14	1.1	10.7	2.5	72.1	31.6	1.8	4.7
Max.	7.6	0.85	31	0.32	3.8	28.9	8.1	251.8	98.9	6.5	19.3
Min.	6.9	0.57	4	0.00	0.5	1.1	0.5	30.3	14.8	0.5	5.1
T 3: Distance (km) = 2.54											
Mean	7.0	0.61	95	0.09	1.7	8.1	5.0	101.4	28.4	5.1	11.3
S D	0.3	0.20	264	0.07	1.7	8.5	3.7	71.7	26.3	2.3	5.2
Max.	7.5	0.87	932	0.17	5.7	25.2	13.4	221.5	80.4	10.3	19.1
Min.	6.4	0.29	5	0.00	0.2	0.7	0.7	7.0	3.4	1.3	5.0
T 4: Distance (km) = 4.61											
Mean	7.1	0.66	11	0.11	6.7	6.5	3.8	87.6	32.5	4.7	12.5
S D	0.3	0.28	5	0.08	12.3	6.8	2.2	80.3	31.4	1.6	4.5
Max.	7.5	1.22	17	0.22	37.0	19.6	7.0	247.9	97.5	6.7	19.0
Min.	6.7	0.31	3	0.02	0.3	0.7	0.1	6.4	3.0	2.1	5.2

Table 5. Results obtained during the monitoring of La Virgen Creek.

V 1: Distance (km) = 0.00											
Parameter	pH	K_E mS/cm	S.S mg/l	Nitrites (mg/l)	Nitrates (mg/l	Ammonia (mg/l)	P (mg/l)	COD (mg/l)	BOD_5 (mg/l)	D O (mg/l)	T (ºC)
Media	7.3	0.74	54	0.03	0.9	10.1	5.7	84.4	18.4	4.9	14.6
S D	0.1	0.03	82	0.04	1.3	10.3	1.6	62.9	9.5	1.5	2.7
Max.	7.4	0.77	328	0.08	2.7	21.8	8.9	143.5	24.6	5.3	16.6
Min.	7.2	0.72	35	0.01	0.4	2.3	5.7	19.4	8.4	3.4	11.6
V 2: Distance (km) = 0.96											
Mean	7.2	0.76	17	0.01	1.0	8.8	7.6	74.3	15.4	3.6	13.1
S D	0.1	0.04	17	0.01	0.3	9.2	1.7	53.6	10.1	1.7	3.2
Max.	7.4	0.80	40	0.02	1.4	21.5	9.4	122.5	29.8	5.5	16.5
Min.	7.1	0.71	3	0.00	0.8	1.6	6.0	20.3	10.2	1.5	9.8
V 3: Distance (km) = 1.68											
Mean	7.2	0.74	7	0.01	10.6	5.4	8.3	70.6	20.4	5.3	12.2
S D	0.1	0.05	3	0.01	16.0	4.0	0.7	60.1	14.7	3.1	2.9
Max.	7.1	0.80	9	0.02	29.0	9.0	8.7	121.6	34.7	9.2	15.5
Min.	7.0	0.70	3	0.00	1.3	1.8	7.5	17.3	5.4	2.0	9.2

Table 6. Results obtained during the monitoring of Fuentecillas creek

F 1: Distance (km) = 0.00									
Parameter	pH	K_E mS/cm	S.S mg/l	Nitrates (mg/l)	P (mg/l)	COD (mg/l)	BOD_5 (mg/l)	D O (mg/l)	T (ºC)
Mean	6.9	0.80	11	5.5	3.4	77.0	21.4	4.8	11.8
S D	0.2	0.06	14	2.8	0.3	12.5	18.3	2.2	4.6
Max.	7.0	0.85	28	8.3	3.7	88.6	40.2	6.6	15.8
Min.	6.7	0.73	2	2.7	3.1	64.7	5.4	2.4	2.8
F 2: Distance (km): 0.67									
Mean	7.1	0.74	2.7	14.7	2.4	56.4	18.1	8.5	10.3
S D	0.1	0.04	2.4	5.4	0.6	27.9	14.4	1.6	4.0
Max.	7.2	0.77	5.2	20.8	3.0	72.8	34.6	9.5	15.5
Min.	6.9	0.70	0.4	10.6	1.8	24.4	9.2	6.7	2.8
F 3: Distance (km): 2.71									
Mean	7.3	0.72	30	8.7	1.0	16.3	7.2	10.6	11.5
S D	0.3	0.06	37	5.6	0.2	22.9	10.2	1.3	4.7
Max.	7.5	0.78	56	12.6	1.2	31.7	14.0	11.5	15.8
Min.	7.1	0.66	4	4.7	0.9	0.8	0.4	9.7	1.2

Table 7. Results obtained during the monitoring of the Guadarrama river

G 1: Distance (km) = 0.00											
Parameter	pH	K_E mS/cm	S.S mg/l	Nitrites (mg/l)	Nitrates (mg/l)	Ammonia (mg/l)	P (mg/l)	COD (mg/l)	BOD_5 (mg/l)	DO (mg/l)	T (ºC)
Mean	7.0	0.42	8	0.35	14.1	3.2	2.6	18.3	6.0	7.4	15.2
S D	0.3	0.06	6	0.22	7.2	2.9	1.2	7.2	5.2	1.6	2.9
Max.	7.2	0.51	17	0.67	22.0	6.4	3.9	28.4	12.7	8.9	19.1
Min.	6.6	0.36	2	0.16	7.9	0.6	1.5	12.3	0.4	5.7	12.3
G 2: Distance (km) = 1.75											
Mean	6.9	0.41	116	0.23	13.3	1.8	2.4	21.5	5.5	7.0	16.3
S D	0.3	0.05	214	0.08	7.0	1.3	1.0	5.4	4.4	1.5	3.5
Max.	7.2	0.47	436	0.28	21.0	3.4	3.4	25.0	10.1	8.6	21.2
Min.	6.6	0.35	3	0.14	7.3	0.7	1.5	14.1	0.3	5.2	13.0
G 3: Distance (km) = 2.45											
Mean	6.7	0.41	8	0.21	12.9	1.3	2.1	14.7	5.0	5.2	16.3
S D	0.2	0.05	8	0.07	6.7	0.9	0.9	6.3	5.3	1.6	3.7
Max.	7.0	0.35	18	0.27	20.0	2.2	3.1	23.1	9.7	6.8	21.5
Min.	6.6	0.46	2	0.14	6.7	0.5	1.3	10.4	0.3	3.6	12.7
G 4: Distance (km) = 3.36											
Mean	6.8	0.40	12	0.22	9.8	1.8	2.2	17.3	4.8	5.8	14.3
S D	0.2	0.04	10	0.08	4.2	1.3	0.7	5.4	4.2	1.4	1.4
Max.	6.9	0.46	26	0.27	13.0	3.5	2.9	23.8	9.6	6.6	15.4
Min.	6.6	0.37	4	0.12	5.0	0.6	1.5	11.8	0.3	3.8	12.2
G 5: Distance (km) = 4.45											
Mean	6.8	0.42	19	0.23	11.6	1.6	1.9	18.5	4.4	5.7	15.5
S D	0.2	0.04	11	0.10	6.3	1.3	0.5	3.9	4.3	1.2	3.8
Max.	7.0	0.46	30	0.29	18.0	3.4	2.3	24.6	8.1	6.9	20.4
Min.	6.6	0.36	5	0.12	5.5	0.6	1.3	15.5	0.3	4.1	11.3
G 6: Distance (km) = 6.00											
Mean	6.8	0.42	21	0.24	11.3	1.8	2.2	15.4	4.0	5.5	15.4
S D	0.3	0.04	14	0.10	5.7	1.3	1.0	4.2	3.5	1.3	3.8
Max.	7.0	0.46	38	0.13	17.0	3.4	3.1	21.3	6.2	6.7	20.3
Min.	6.5	0.36	6	0.32	5.7	0.6	1.1	11.7	0.5	4.0	11.1
G 7: Distance (km) = 7.4											
Mean	6.8	0.41	19	0.23	11.0	1.5	1.8	13.8	3.8	5.8	15.5
S D	0.2	0.04	11	0.10	5.3	1.2	0.4	3.9	4.0	1.3	3.8
Max.	7.0	0.44	30	0.29	15.0	3.2	2.1	20.1	5.6	6.9	20.4
Min.	6.6	0.36	5	0.12	5.1	0.5	1.2	13.5	0.2	5.1	11.3

Table 8. Summary of the organic loads of the Guadarrama river

Organic loads (kg BOD_U/d)	Value
$L_{G\ 1}$	1064.5
$L_{T\ 4}$	136.3
$L_{V\ 3}$	32.1
$L_{F\ 3}$	4.7
$L_{G\ 7}$	441.8
L_R	795.8

Figure Captions

Figure 1. Map of the Guadarrama river course.

Figure 2. Course of the Guadarrama river and its influents with indication of the sampling points (G: Guadarrama river; M: Motilona creek; T: La Torre creek; V: La Virgen creek; F: Fuentecillas creek).

Figure 3. COD, BOD_5, *WQI, DO* and *D* variation in Motilona creek.

Figure 4. COD, BOD_5, *WQI, DO* and *D* variation in La Torre creek.

Figure 5. COD, BOD_5, *WQI, DO* and *D* variation in La Virgen creek.

Figure 6. COD, BOD_5, *WQI, DO* and *D* variation in Fuentecillas creek.

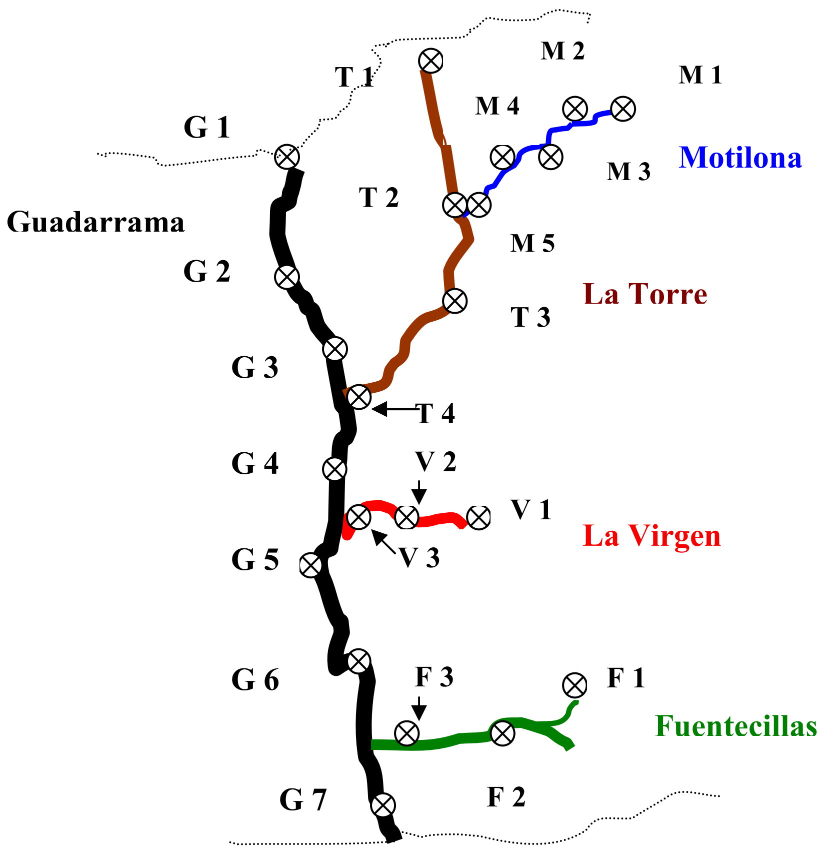
Figure 7. COD, BOD_5, *WQI, DO* and *D* variation in the Guadarrama river.

Figure 8. Determination of the BOD_U removal constant.

Figure 9. Linear correlation between *D* and *WQI*.


MADRID
Cercedilla
Guadarrama
Collado Villalba
Galapagar
Torrelodones
Las Rozas
Villaviciosa de Odón
Navalacarnero
Carranque
Bargas
TOLEDO
Toledo
Guadarrama River

Figure 1.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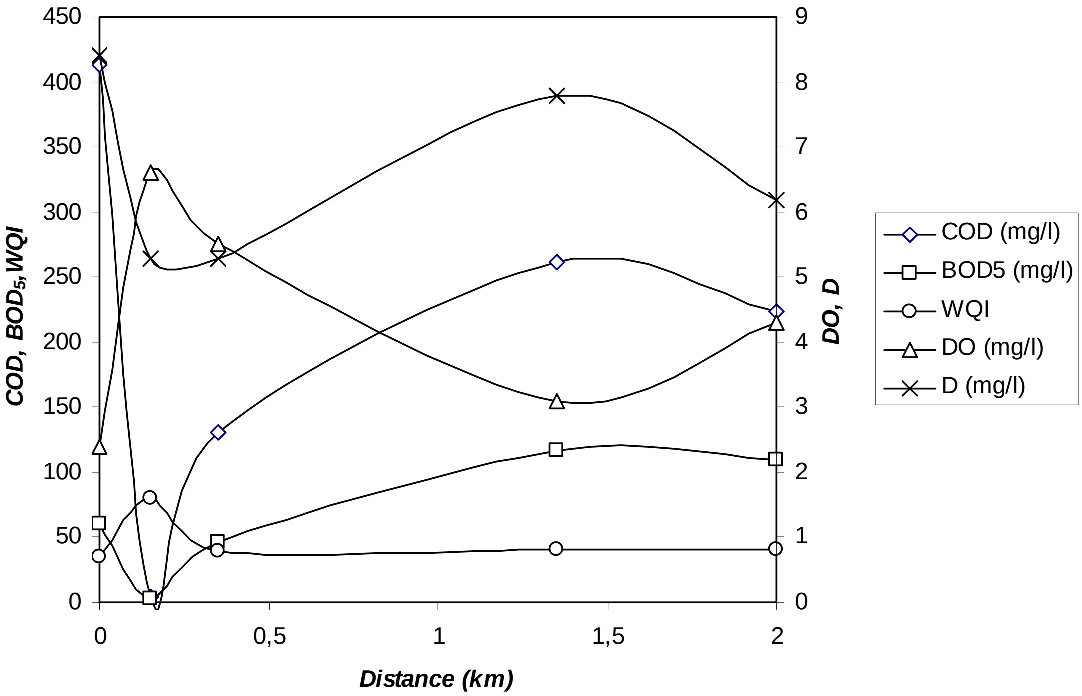
T 1
M 4
G 1
Motilona
M 3
T 2
Guadarrama
M 5
G 2
La Torre
T 3
G 3
T 4
G 4
V 2
V 1
La Virgen
V 3
G 5
G 6
F 3
F 1
Fuentecillas
G 7
F 2

Figure 2.



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400
350
300
250
200
150
100
50
0
9
8
7
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5
4
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2
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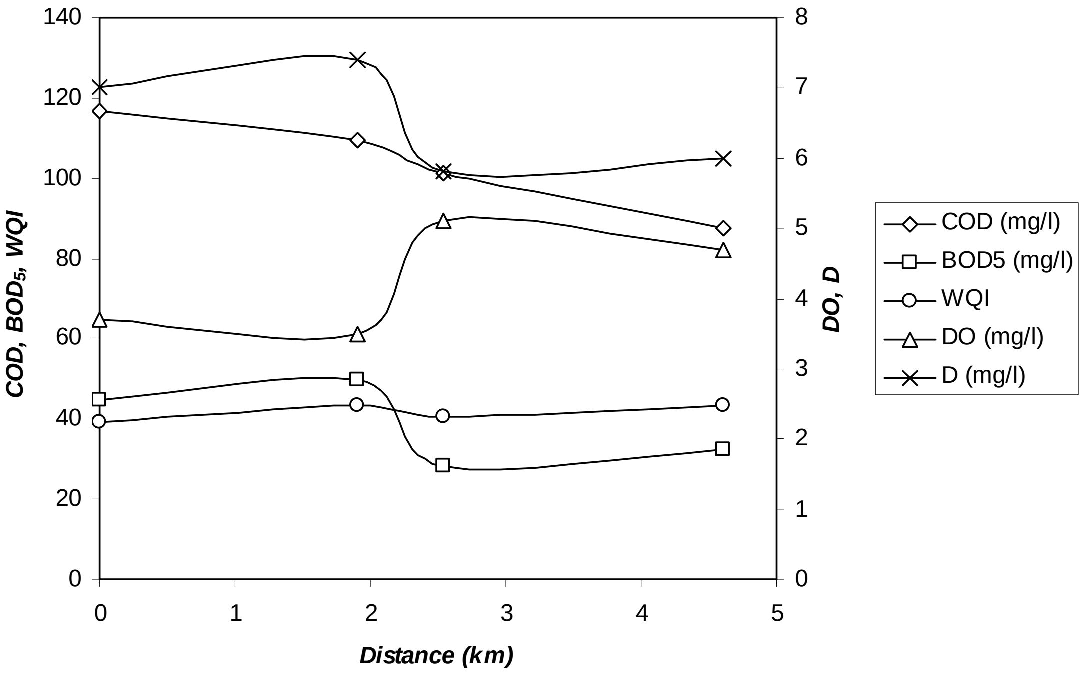
0
0,5
1
1,5
2
COD, BOD5, WQI
DO, D
Distance (km)
COD (mg/l)
BOD5 (mg/l)
WQI
DO (mg/l)
D (mg/l)

Figure 3.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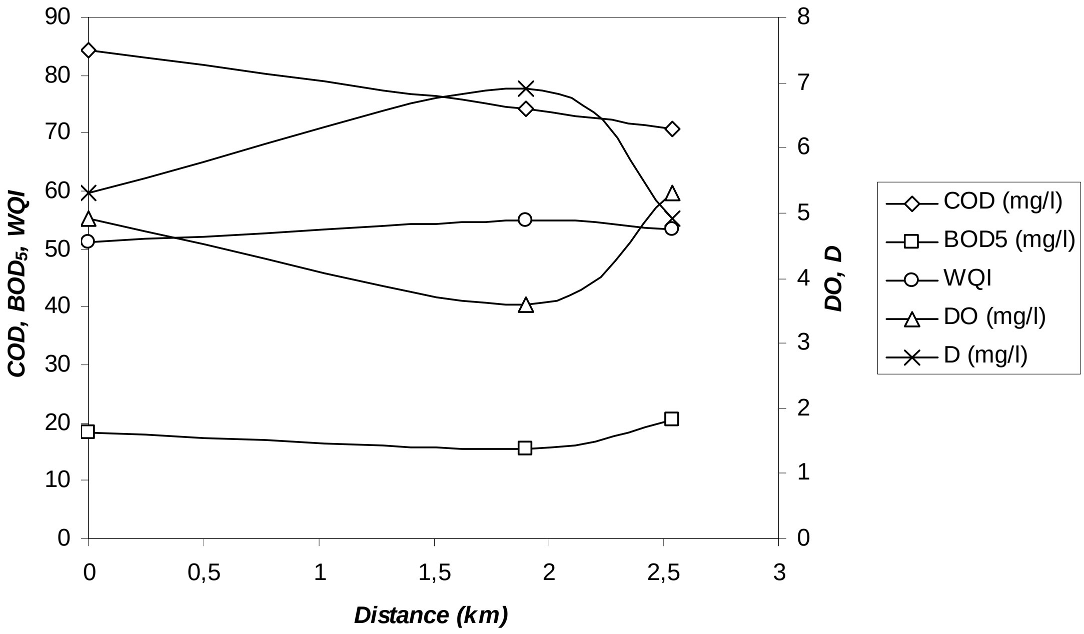
4
5
Distance (km)
COD, BOD5, WQI
DO, D
COD (mg/l)
BOD5 (mg/l)
WQI
DO (mg/l)
D (mg/l)

Figure 4.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0
COD, BOD5, WQI
8
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DO, D
0
0,5
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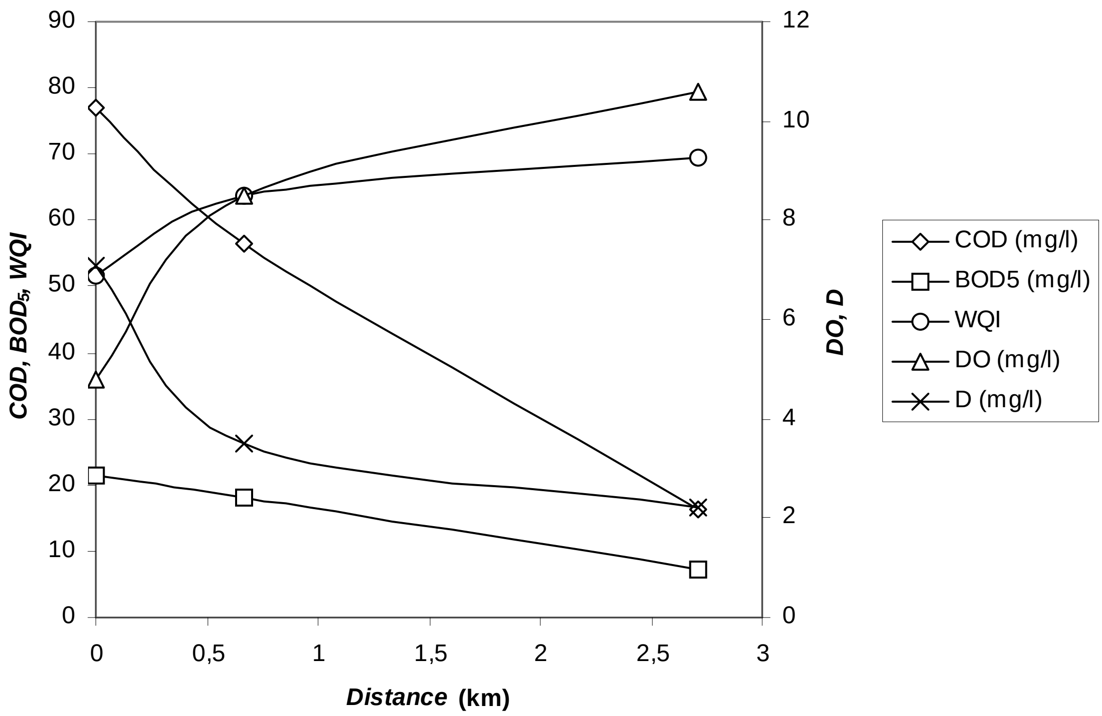
1,5
2
2,5
3
Distance (km)
COD (mg/l)
BOD5 (mg/l)
WQI
DO (mg/l)
D (mg/l)

Figure 5.



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4
2
0
0
0,5
1
1,5
2
2,5
3
COD, BOD5, WQI
DO, D
Distance (km)
COD (mg/l)
BOD5 (mg/l)
WQI
DO (mg/l)
D (mg/l)

Figure 6.

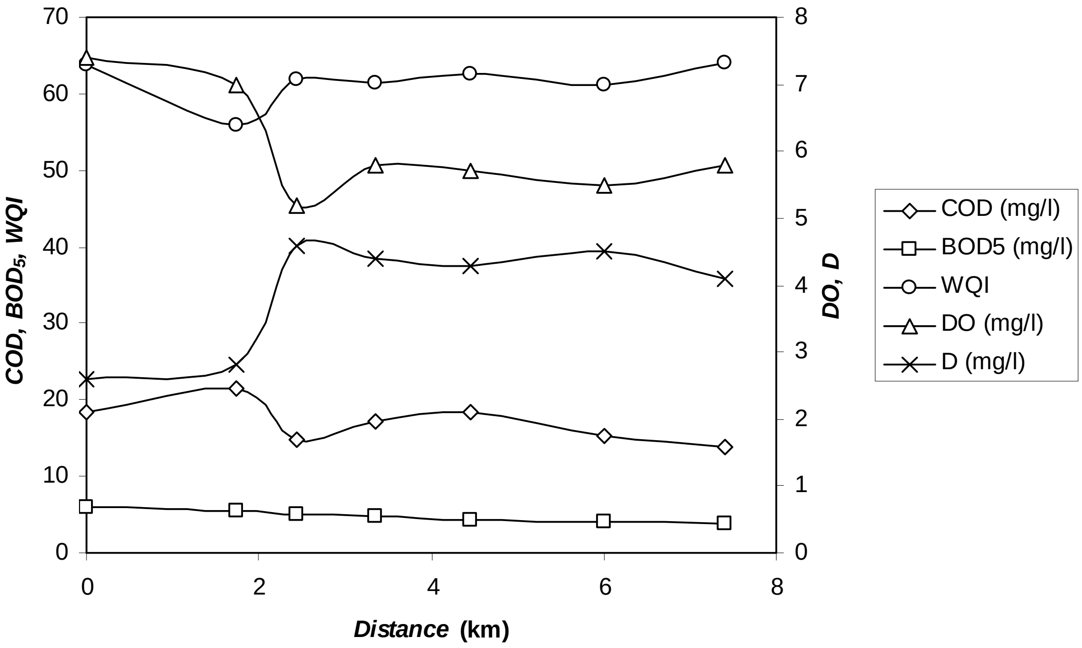
70
60
50
40
30
20
10
0
8
7
6
5
4
3
2
1
0
0
2
4
6
8
COD, BOD5, WQI
DO, D
Distance (km)
COD (mg/l)
BOD5 (mg/l)
WQI
DO (mg/l)
D (mg/l)

Figure 7.

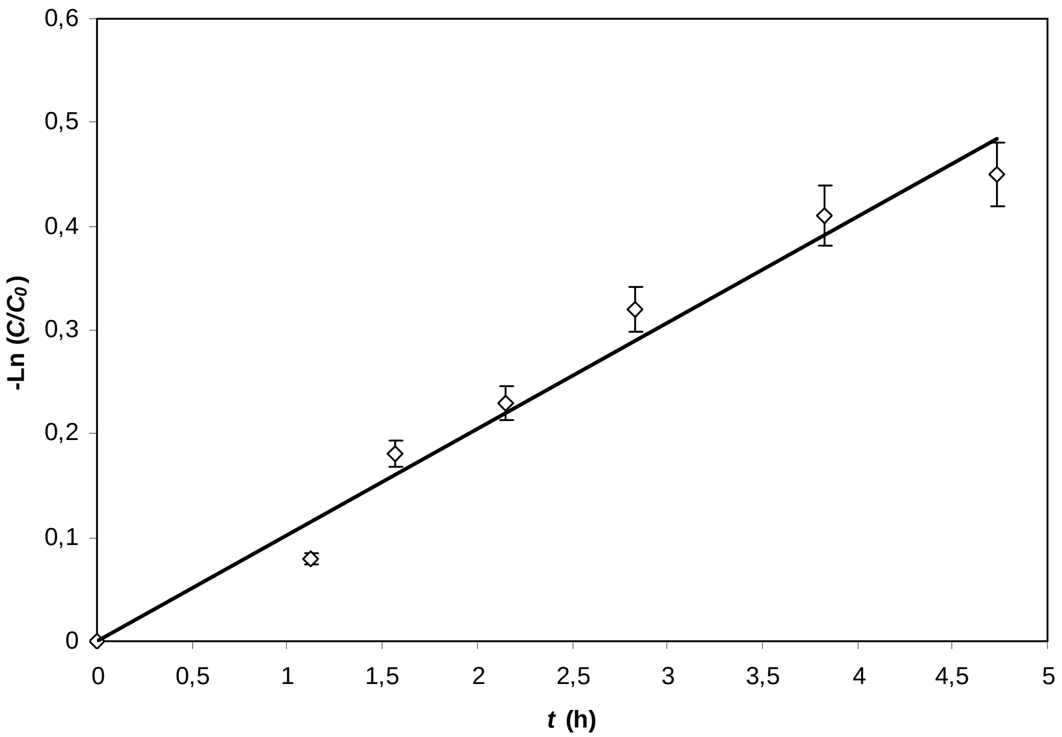

Figure 8.

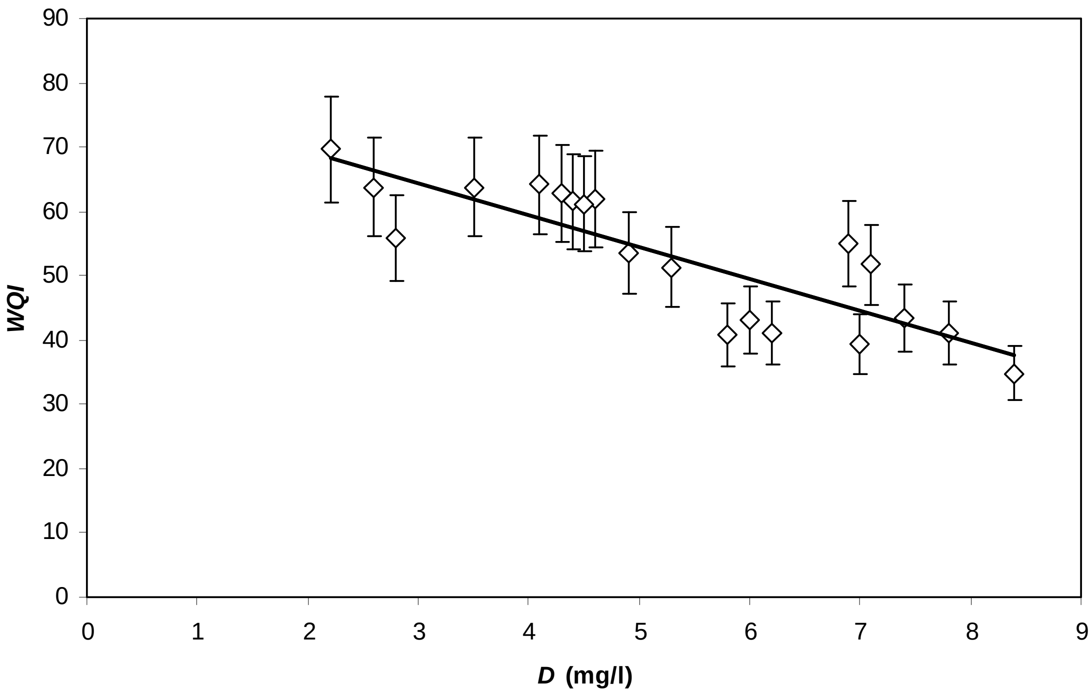

Figure 9.