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Managing water quality under drought conditions in the Llobregat River Basin

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HIGHLIGHTS

- Water allocation and mechanistic water quality models have predictive capacities.
- Water management has a large effect on the water quality state.
- An integrated model for water allocation and quality in river basins is proposed.
- We test different water management and quality measures to ease drought effects.
- Combining both types of measures allows adapting responses to drought evolution.

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ABSTRACT

The primary effects of droughts on river basins include both depleted quantity and quality of the available water resources, which can render water resources useless for human needs and simultaneously damage the environment. Isolated water quality analyses limit the action measures that can be proposed. Thus, an integrated evaluation of water management and quality is warranted.

In this study, a methodology consisting of two coordinated models is used to combine aspects of water resource allocation and water quality assessment. Water management addresses water allocation issues by considering the storage, transport and consumption elements. Moreover, the water quality model generates time series of concentrations for several pollutants according to the water quality of the runoff and the demand discharges. These two modules are part of the AQUATOOL decision support system shell for water resource management. This tool facilitates the analysis of the effects of water management and quality alternatives and scenarios on the relevant variables in a river basin.

This paper illustrates the development of an integrated model for the Llobregat River Basin. The analysis examines the drought from 2004 to 2008, which is an example of a period when the water system was quantitative and qualitatively stressed. The performed simulations encompass a wide variety of water management and water quality measures; the results provide data for making informed decisions. Moreover, the results demonstrated the importance of combining these measures depending on the evolution of a drought event and the state of the water resources system.

1. Introduction

Droughts involve a decrease in water resource availability that is primarily related to a long-term reduction in precipitation (Mishra and Singh, 2010). Droughts can continue for months or even years, leading to social and environmental problems. Solutions to alleviate the effects of droughts are typically difficult and expensive. Hence, because droughts are expected to increase in frequency, intensity, and magnitude with climate change, understanding their effects on diverse aspects of river systems is imperative (Elsdon et al., 2009). Droughts affect water supply and deteriorate water quality (Riebsame et al., 1990), which make water resources useless for economic activities and human water supply.

Several studies have been performed regarding the effects of droughts on human and environmental needs, primarily regarding water scarcity (Susnik et al., 2012), which is compounded by droughts. Other studies have reported on the effects of droughts and inherent low-flow conditions on river ecosystems (Lake, 2003; Boix et al., 2010).

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However, most of these studies focused on the characterisation of water quality changes using monitoring techniques (Caruso, 2002; Van Vliet and Zwolsman, 2008; Whitworth et al., 2012). Moreover, the majority of studies that utilised models to make inferences about the importance of droughts on water quality have typically applied empirical approaches (Attrill and Power, 2000). Unlike empirical models, mechanistic models that are based on physical and chemical principles are assumed to have some predictive capabilities (Warfvinge, 1995). Presently, many river water quality models are available; a review of these models can be found in Cox (2003). Among these models, the QUAL2 family of models (Chapra and Pelletier, 2003) is one of the most commonly used (Capodaglio et al., 2005). Other traditional models, such as WASP (Ambrose et al., 1987), CE-QUAL-RIV1 (Environmental Laboratory, 1995), and QUASAR (Whitehead et al., 1997), have been used depending on data availability, the nature of the analysed problems, or the knowledge of the users (Paredes et al., 2010). These types of water quality models can shed light on the difficult problem of managing water quality problems in complex river basins during droughts.

Mechanistic water quality models provide insights on the effects of action measures on the concentrations of pollutants in a river system, focusing specifically on actions that are related to water quality (e.g., waste water treatment improvements). Nevertheless, the potential of these tools can be widened by jointly applying mechanistic models with water resource management models, which are similar to the widely known SIM V (Martin, 1983), MODSIM (Labadie, 1992) or WEAP (Grigg, 1996) models. In this manner, water management measures can also be tested in relation to water quality improvements (e.g., minimum flows in rivers). In fact, water quality problems are often associated with flow fluctuations in rivers (Stow and Borsuk, 2003). According to Towler et al. (2010), there is a need to fully couple climate, streamflow, and water quality assessment components to ensure a complete range of potential effects for planning strategies. Therefore, an integrated water management and water quality model would be useful for performing different tests in water resource systems. Previous works have addressed the integrated modelling of water quantity and quality (Even et al., 2007; Paredes-Arquiola et al., 2010; Paredes et al., 2010; Ferrer et al., 2012). Nevertheless, these studies did not focus on the specific problem of drought management, i.e., in which both water scarcity and pollution can largely hinder the functionality of an entire river basin. Presumably, the integrated assessment of water management and water quality would generate useful data that can be used to confront drought situations using all available means.

We propose to use integrated models for water management and water quality for evaluating the evolution of pollutants in river systems during drought periods in diverse action measure scenarios, including water management and water quality measures. Therefore, the paper firstly describes two coupled models; the resulting integrated methodology is also presented. Next, the model's applicability is illustrated with a case study in the Llobregat River Basin, where water scarcity and water quality problems are often substantially aggravated during drought periods. The results illustrate that the conjunctive analysis of water management and water quality can help solve real problems in complex water resource systems under drought conditions. Finally, the conclusions present relevant reflections on the results obtained in this study.

2. Material and methods

2.1. Integrated model

A methodology comprising two coordinated models is used to integrate aspects of water resource allocation and water quality assessment. These two modules are part of the AQUATOOL decision support system shell (Andreu et al., 1996) for water resource planning and management, which facilitates analyses on the effects of multiple management alternatives and scenarios on the relevant variables in a river basin. Thus, it is easier to conduct trade-off analysis, risk evaluations, and other useful processes that provide data for making informed decisions. AQUATOOL is a geo-referenced database that can be applied to nearly any river basin or water resource system type. The database provides a common interface, data and result management tools for the different modules. This decision support system has been developed for more than 20 years and follows well-established methodologies for water resource system analysis, which was demonstrated via its application in most river basin districts in Spain.

SIMGES (Andreu et al., 2007) is a water management simulation model that optimises monthly water resource allocations at the river basin scale. This module solves a conservative flow network that contains storage, transport, diverting, consumption, and return elements. These features are based on the reality of the modelled system and must be defined and calibrated by the user. For each time step of the simulation, the flow network algorithm determines the flows in the system while trying to satisfy multiple objectives, e.g., deficit minimisation, maximum adaptation to the reservoir target volume curves and the hydropower production objectives.

GESCAL (Paredes-Arquiola et al., 2010) is a water quality simulation model that allows analysis on water quality evolution in rivers, reservoirs and entire water resource systems according to the water quality of the runoff and the demand discharges. GESCAL simulates temperature, biochemical oxygen demand (BOD), dissolved oxygen, organic nitrogen, ammonium, nitrates, organic phosphorous, phosphates, Chlorophyll-a, toxins (e.g., heavy metals and organic compounds) and arbitrary constituents. One-dimensional and pseudo-stationary conditions are assumed for water quality in rivers. In reservoirs and lakes, water quality can be represented as a continuously stirred tank or as a two-layer model that includes the epilimnion and hypolimnion. Further details on the formulation of the model can be found in Paredes-Arquiola et al. (2010).

Because the models are integrated in the same platform, the results are easily transferred and recurrent simulations are permitted, which are useful to perform scenario analysis. In this case, the results of the SIMGES model contain the monthly time series of the relevant variables related to water management, such as the ratio of supply to demand, volumes stored in reservoirs, flows in the rivers, and/or hydropower production. Moreover, the model also provides indicators for the water supply reliabilities and vulnerabilities, which represent the level of satisfaction of water demands over the entire simulated period. GESCAL uses the flow results for rivers and reservoir volumes from the SIMGES module. Hence, the simulation period is the same for both models. The results of the GESCAL model are the time series of the pollutant concentrations along each river stretch and the time series of pollutant concentrations in each layer of the reservoirs.

2.2. The Llobregat River Basin

The Llobregat River Basin (LRB) is located in northeastern Spain and flows into the Mediterranean Sea. The basin covers 4957 km^2 and has a mean annual precipitation of 704 mm, which produces a mean annual inflow of 694 Mm^3 in unpaired conditions. The main tributaries of the Llobregat River are the Cardener and Anoia Rivers. Groundwater resources account for 22% of the total available resources in the basin.

Several highly populated cities with important industrial activities are located throughout the river basin. Consequently, the majority of water resources are devoted to urban supplies, which generate large amounts of wastewater that pour into the system. Another water demand, which is substantially smaller than the urban demands, is irrigated agriculture, which is primarily performed in local areas, such as Anoia, near Manresa town and mostly in the lower portion of the river basin. Although this use is primarily located in the lower basin, i.e., near the river mouth, agriculture produces diffuse pollution that alters the water quality in these areas. Salt mining activities are located in

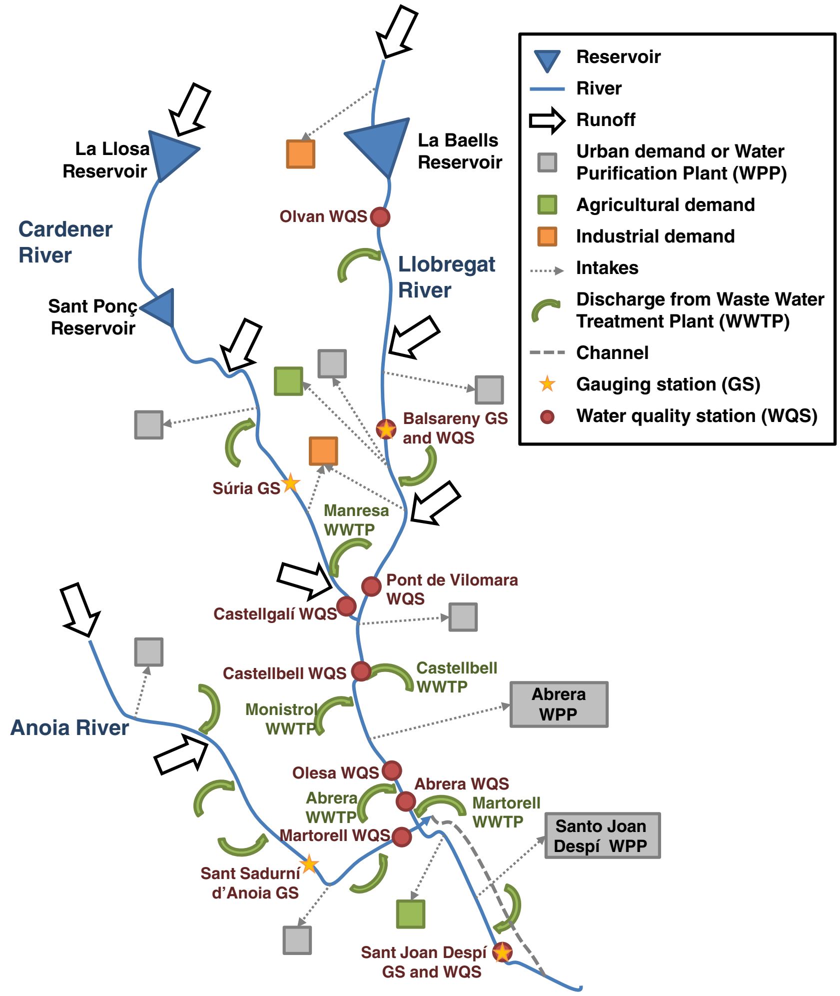

Fig. 1. Llobregat River Basin diagram.

the middle reaches of the Llobregat and Cardener Rivers. While these activities have a small water demand, they produce largely contaminate waste (primarily from chlorides and potassium) that is deposited in the basin. Finally hydropower production demands are located along the main river course (106 small hydropower stations are currently in use). Fig. 1 shows a simplified diagram of the river basin that includes its main elements. More information on human pressures in the LRB can be found in Munné et al. (2012).

To reduce the effects of the different water discharges on the river system, there are several infrastructures to collect the discharges. There is a channel that receives waste material from the salt mining and industrial activities and leads them to the Mediterranean Sea. Another channel that flows parallel to the Llobregat River (east side) collects water from the Anoia River and the Rubí stream (which is largely affected by industrial activities; more water is collected from the stream than the river) and returns it to the Llobregat River directly upstream from the mouth. Although the river quality has recently improved (Munné et al., 2012), many discharges, their compositions, and the effects of groundwater affect water quality conditions in the middle to lower reaches of the river. Here, moderate and occasionally high concentrations of ammonium, nitrates, phosphorous and salts are found, which is problematic for the urban water supply and causes both an increase in water treatment requirements in the main water purification plants (WPPs) and environmental effects. The situation worsens during drought episodes, i.e., when the river flows are lower. In fact, the LRB suffers from recurrent drought periods, which generate both water quantity and quality problems. The last drought episode occurred from 2004 to 2008. Serious social, political and economic consequences transpired as a result of this drought event.

Monthly river flow data from gauged stations were available for several locations in the LRB from 2001 to 2011. In some ungauged areas, inflow data were obtained from a mass balance approach to determine the inflow from gauged stations or from a rainfall runoff model (Catalan Water Agency, 2010). Regarding water quality, data for the effluents from the wastewater treatment plants (WWTPs) were available from 2002 to 2008. Monthly data for the pollutant concentrations in rivers existed from 2002 to 2008 at 13 water quality stations (WQS). Moreover, the Catalan Water Agency exploitation records were used to obtain information regarding the water demands and the management rules that were applied during the studied period.

3. Case study

We propose a methodology that is based on the presented tools to analyse different alternatives for coping with the drought situation in the LRB. The method consists of three consecutive steps (see Fig. 2). First, the water management and water quality models are calibrated and validated. It is crucial to include the analysed drought period in the calibration and validation data to ensure that the models adequately represent the performance of the system in the specific situation. The results from STEP 1 represent the baseline situation, which is used as the reference scenario. The analysis of the calibration data and the initial results provides important information for recognising the main problems in the basin. In STEP 2, the action measures are designed and

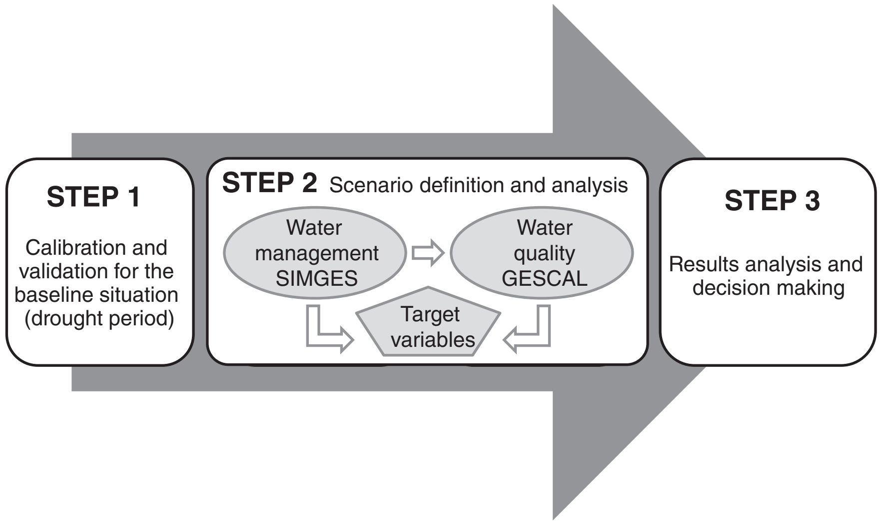

Fig. 2. Methodology for integrated drought management in the Llobregat River Basin.

combined to generate reasonable and realistic scenarios that are in line with the identified casuistry. The measures that can be simulated are related to either water quantity or water quality. It is important to select proper output variables (target variables) that represent the evolution of the addressed problems. Finally, STEP 3 encompasses the analysis of the target variables for the action measures or sequence of action measures that best facilitate the mitigation of drought effects.

The water management and water quality models contained in AQUATOOL were implemented for specifically studying the LRB. The calibration period encompassed 4 years, while the validation period covered 2 years. Both phases included part of the drought period from 2004 to 2008 (see Fig. 3).

3.1. Development of the models

A water allocation model for the LRB was provided (calibrated and validated) by the Catalan Water Agency. This model included all relevant water management characteristics for the water resource system, e.g., primary water demands, reservoirs, and channels. Groundwater is important in the river basin; however, it is used locally for a few demands and is not globally managed. Hence, only the pumps in a large aquifer in the lower reaches of the basin (Delta del Llobregat) are considered. Apart from that, the interaction between surface and groundwater (i.e. percolation and discharges from aquifers to the river) are represented in the runoff series entering the managed water resources system. To extend the water allocation model for water quality modelling, it was necessary to introduce new nodes, conductions and discharges from the WWTPs. The water quality of the natural runoff was obtained from the water quality stations and contained the effects of groundwater discharges. A total of 77 river segments were defined in the final model. From these segments, 44 represented the Llobregat River, 15 were from the Cardener tributary, and 18 denoted the Anoia tributary. The criterion for defining river segments was based on changes in the hydraulic features, discharges of point loads, water quality

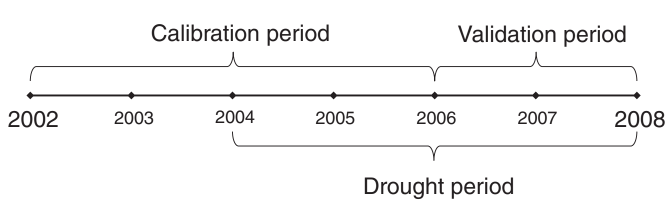

Fig. 3. Calibration, validation and drought periods.

stations or other particularities. Thereafter, it was indispensable to ensure that the modifications introduced in the model did not alter the water balance. Moreover, it was important to confirm that the functionalities of the system in both reality and in the model were analogous. Therefore, we compared the real flows gauged at several locations along the river (blue colour in Fig. 4) with the flows predicted for the same locations (red colour in Fig. 4).

The downstream calibration points accumulated noticeably more errors. For example, the differences in Sant Joan Despí may be partially explained by the errors introduced by the Anoia River subsystem. The uncertainties in this subsystem were related to the large influence of the discharge from the city of Igualada, the effects of an aquifer and the lack of real data for flows in the lower part of the river. These differences may lead to the overestimation of low flows at Sant Joan Despí, which may affect the performance of the water quality model. Hence, these effects must be considered when calibrating the water quality model.

The water quality model was implemented to determine the evolution of BOD, dissolved oxygen, organic nitrogen, ammonium, nitrate, conductivity, and phosphate concentrations. The processes considered included degradation and sedimentation of BOD, aeration and sediment oxygen demand, degradation and sedimentation of organic nitrogen, nitrification of ammonium, denitrification of nitrates, and sedimentation and/or degradation of phosphates. Dissolved salts were considered as conservative pollutants (see Fig. 5).

The calibration consisted of a trial and error method that was combined with an automatic calibration procedure based on the SCEUA optimisation algorithm (Duan et al., 1992). The water quality measurements were considered to be representative values for an entire month because the GESCAL model functions on a monthly stationary basis. Therefore, for stations that exhibit large variability in concentrations, the calibration should be analysed using tendencies instead of looking for perfect matches. The resulting calibrated parameters had typical values except for ammonium nitrification, which, was very high along some stretches. This difference may be explained by the large amount of ammonium with a high potential for nitrification discharged from the WWTPs into the river. According to Fig. 6, the water quality tended to deteriorate moving downstream. In general, the calibration results for the water quality model were satisfactory. Detailed information about the calibrated parameters and more calibration graphics are presented in the Appendix.

The validation of both models also produced acceptable results, with correlation coefficients ranging from 0.76 to 0.95 for the water allocation model and from 0.64 to 0.88 for the water quality model. Therefore,

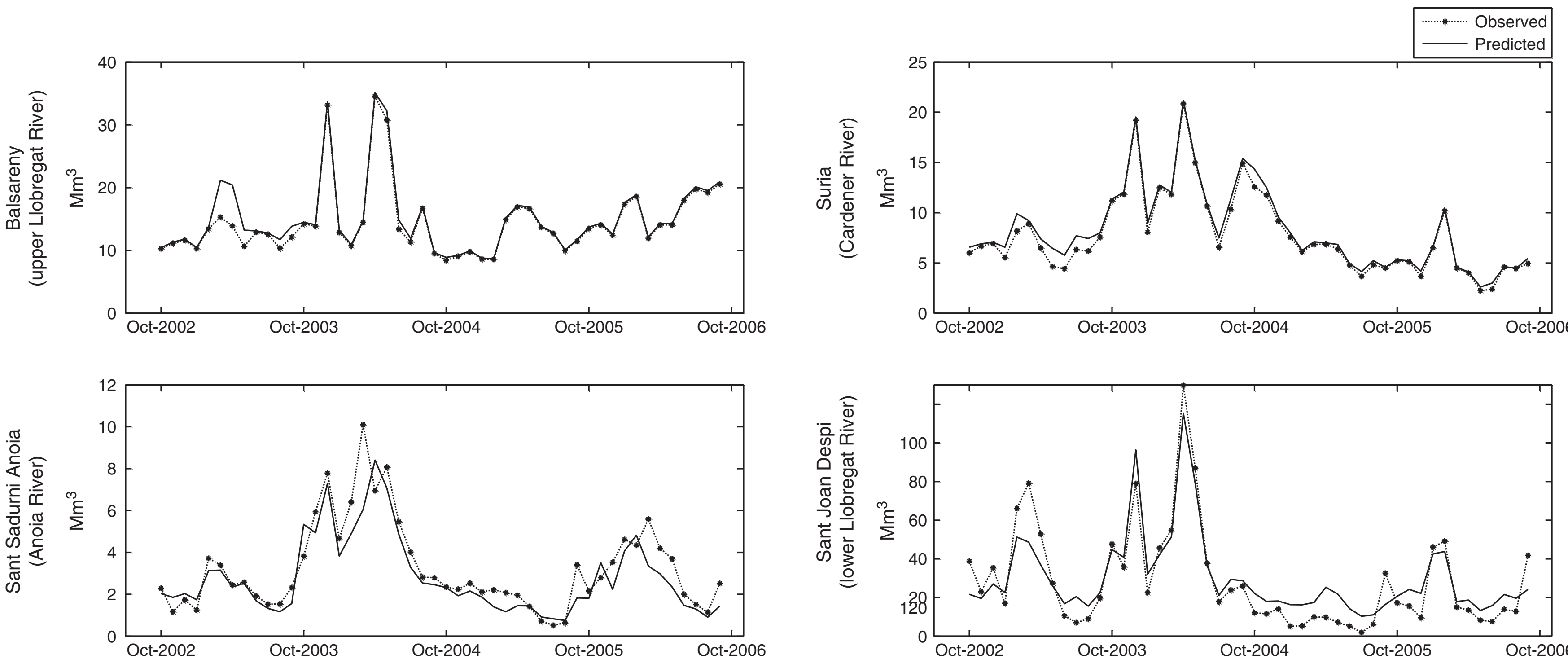

Fig. 4. Calibration plots for the water management model. Streamflows are shown for four sites within the LRB.

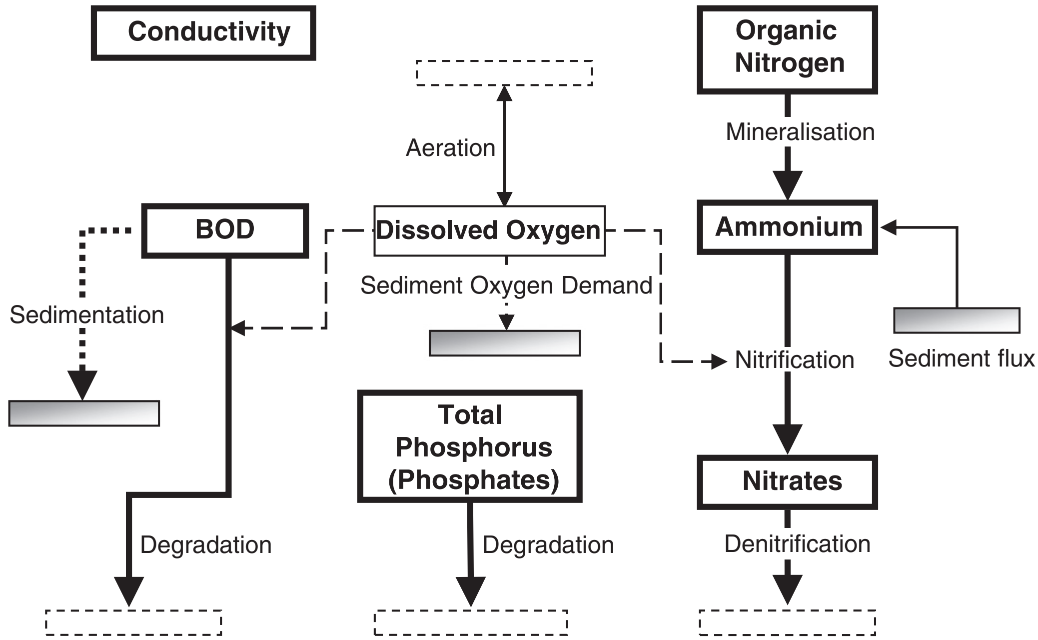

Fig. 5. Water quality constituents considered in the LRB.

the integrated model for simulating water management and water quality in the LRB was ready for applications.

3.2. The effects of drought

The aforementioned methodology was first used to analyse the effects of the most recent drought period (October 2004 to September 2008). The upper reaches of the Llobregat River exhibited flows of approximately 8–9 Mm^3/month between October 2004 and February 2005 and 6 Mm^3/month during the 2007–2008 winter. In the lower reaches, the flows were more irregular with minimum values of approximately 10 Mm^3/month in July 2005 and in the winter of 2007–2008. In the Cardener River, low flows began in early 2005 and continued until the end of April 2008. The flows in the Anoia River, which is not regulated and is largely affected by groundwater, reflected the typical recession curve of the aquifer. In this subsystem, it was possible to distinguish between the first period of low flows that began in autumn of 2004 (continuing for one year) and the longer period from the summer of 2006 to the spring of 2008.

Regarding the ratio of supply to demand, urban uses were almost entirely satisfied because they have the highest priority. The only supply deficit of 53.2 Mm^3 occurred between October 2007 and September 2008, considering that the annual urban demand is approximately 390 Mm^3. Otherwise, the agricultural demands, which have an annual demand of 33 Mm^3, suffered from a reduction in the water availability due to their lower priorities. The total deficit that accumulated over the 4-year period was 24 Mm^3; 16 Mm^3 of this deficit occurred in 2007–2008.

The effects of the drought on water quality varied depending on the analysed location and chemical parameters. The results were examined using the WQS that were employed for the calibration; the results are summarised in Table 1. The most affected site was the Martorell WQS because the Anoia River is typically the most polluted water body in the area. The dissolved oxygen concentration, with minimum values of 2.26 mgO_2/L, is a good indicator of the poor water quality in this tributary. The Martorell WQS exhibited the highest values for the other water quality variables. Therefore, a portion of the Anoia streamflow has been historically diverted to a channel instead of being discharged into the Llobregat River.

The water quality in the Cardener River (Castellgalí) became substantially affected by the irrigation area of Manresa, exhibiting large nitrate, ammonium and phosphate concentrations. The runoff from the salt mines caused high conductivities at the Castellgalí and Pont de Vilomara WQSs, which were approximately 900 μS/cm under normal conditions. The conductivities were large for all of the downstream sites. The Sant Joan Despí WQS experienced the combined upstream effects. Here, the ammonium and phosphate concentrations reached moderate and high values, with maximum values of 3 mg NH_4^+/L and 0.9 mg P_2O_5/L, respectively. These high concentrations posed occasional problems for the Sant Joan Despí WPP, especially when the ammonium concentration exceeded 5 mg NH_4^+/L.

From the aforementioned results, the water quality of the LRB is affected by droughts. To minimise these effects, a scenario analysis was conducted using the integrated model for water management and water quality; different action measures for alleviating the drought effects were simulated. According to the obtained results, the variables that provide the largest system-wide improvements include the total supply deficit accumulated during the drought, which indicates water management, and the BOD, ammonium, and dissolved oxygen concentrations and the conductivity, which are good water quality indicators. Therefore, these variables are the targets that must be considered in the different scenarios.

3.3. Scenario analysis and discussion

3.3.1. Reservoirs management

During the drought period, natural streamflows decreased and the flows discharged by the WWTPs represented a larger proportion of the total river flows. These changes caused a decrease in the dilution capacity and subsequent water quality effects. There are several options for increasing the proportion of natural flows in a river. However, most of these options require long-term planning and detailed studies (e.g., inter-basin transfers or water reuse). An easy short-term alternative for achieving this goal consists of forcing minimum flows downstream of the reservoirs, i.e., La Baells and Sant Ponç.

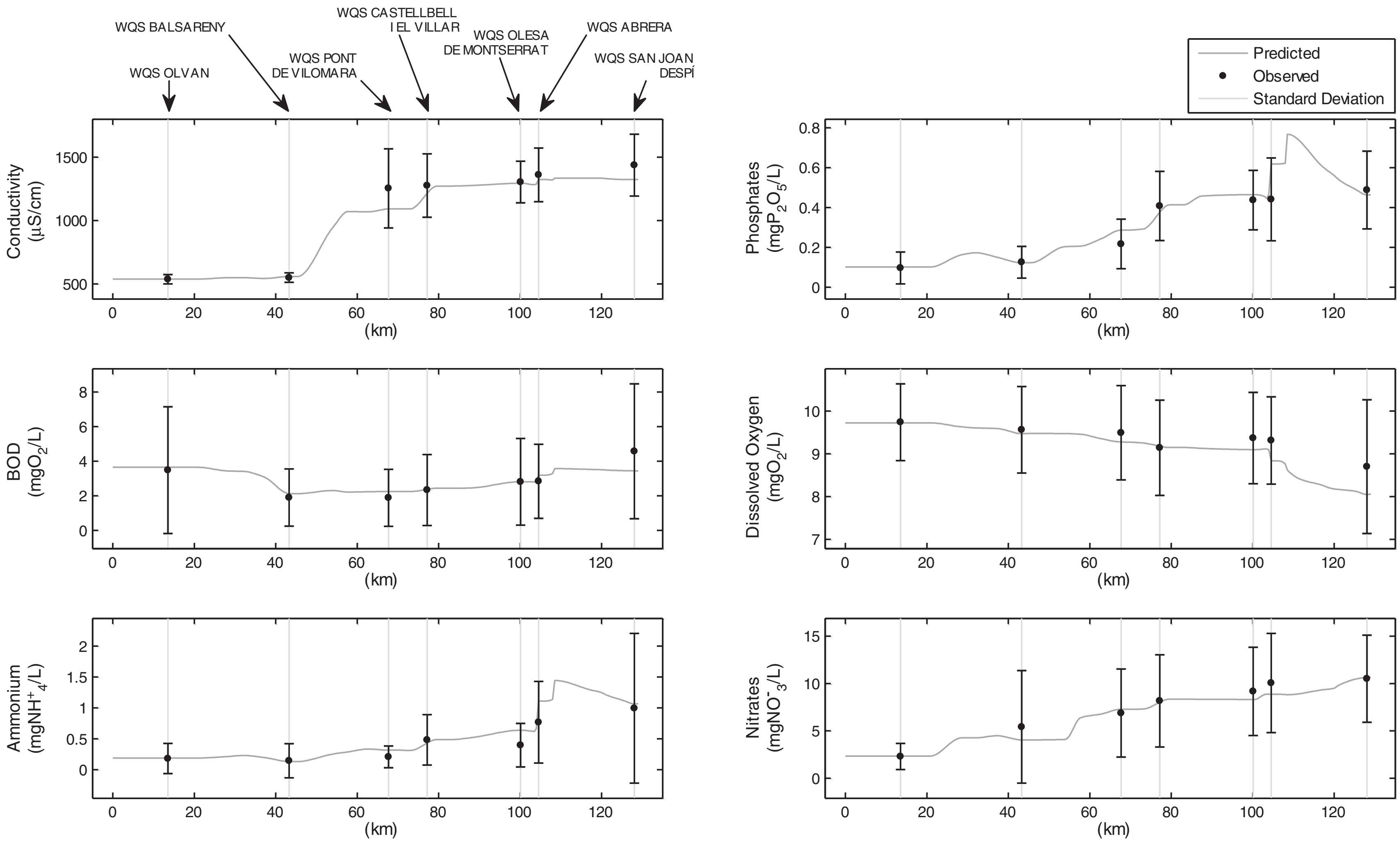

Fig. 6. Comparison between observed and predicted water quality characteristics for a few WQS along the Llobregat River.

Table 1
Summary of the water quality model results at some WQS of the LRB for the drought of 2004–2008.

			Llobregat River			Cardener River	Anoia River
			Pont de Vilomara	Olesa	San Joan Despí	Castellgalí	Martorell
BOD	mgO_2/L	Average	2.19	2.53	3.17	2.33	4.58
		Maximum	6.02	4.37	4.93	3.72	11.00
Dissolved oxygen	mgO_2/L	Average	9.21	8.96	8.13	8.73	7.86
		Minimum	6.80	6.81	4.82	6.64	2.26
Ammonium	$mgNH_4^+/L$	Average	0.33	0.63	0.92	0.96	1.65
		Maximum	1.01	1.84	3.03	3.07	5.72
Nitrates	$mgNO_3^-/L$	Average	6.96	9.77	11.63	15.17	17.42
		Maximum	14.75	22.84	22.14	54.36	33.03
Phosphates	mgP_2O_5/L	Average	0.30	0.40	0.43	0.92	1.29
		Maximum	0.77	0.84	0.97	3.11	1.83
Conductivity	µS/cm	Average	1126.10	1197.30	1243.00	1329.70	1870.20
		Maximum	1793.90	1612.20	1653.90	1949.40	2801.40

Simulations were performed by changing the flows released from the reservoirs from 0.5 to 5 Mm^3/month in increments of 0.5 Mm^3/month. However, changing the flows may induce future problems with satisfying water demands due to the loss of hyper-annual storage. Therefore, the effects of an action measure should be analysed either in the context of the ratio of supply to demand or the water quality by considering the various chemical parameters. Other ecosystem effects from increasing river flows, such as fish habitats and ecological quality, were not considered in this analysis.

By assessing the changes in the target variables, a considerable effect on the supply to demand ratio was observed. The accumulated deficit for all demands during the drought period surpassed 10 Mm^3 (Fig. 7). The increase in the deficit for the urban demands represented 0.9% of the annual urban demand, while the agricultural deficit accounted for 40% of the annual irrigation demand.

With regard to water quality, the results confirm that the streamflows exhibited pronounced effects on the considered pollutants (Fig. 8). However, depending on the specific site, the results varied. For example, the upstream sites located near the confluence of the Llobregat and Cardener Rivers exhibited different responses. Specifically, the concentrations at Pont de Vilomara remained nearly constant as the flow increased; however, the conductivity decreased substantially. In contrast, the concentrations at Castellgalí were more sensitive to the increased flows, especially the conductivity. Moreover, the ammonium concentrations decreased below 1 $mgNH_4^+/L$ only when the releases exceeded 4 Mm^3/month. Furthermore, in the lower reaches of the Llobregat River, the evolution of all target variables at the Olesa site presents an interesting problem; this site had the highest gradients among all of the sites. At Sant Joan Despí, a similar problem occurred with the ammonium concentrations; the concentrations reached 1 $mgNH_4^+/L$ only for the maximum flow scenario. While it is possible to increase the flows released from the reservoirs to achieve better results, all of the variables except the conductivity appeared to stabilise at approximately 4.5 Mm^3/month. Therefore, further increases in the released flow would have only minor effects.

These results demonstrate that forcing minimum flows downstream of the heading reservoirs is a valid approach for alleviating serious short-term water quality situations; however, it is not a reasonable permanent strategy. On one hand, the supply deficits increase, which primarily affect the agricultural demands; on the other hand, water quality in the lower reaches of the Llobregat River remain unsatisfactory.

3.3.2. Non diversion of the Anoia River flows

Increasing the available water resources in the LRB addresses the water scarcity problem caused by the drought. In the short term, resources can be increased by diverting the flow of the Anoia River to the Llobregat River. However, given the poor water quality of this tributary, it is expected that this action measure may act to decrease the water quality.

Using this alternative approach, the global deficit in the supply to demand ratio was reduced. Nevertheless, the reduction was not substantial (1.35 Mm^3) because the contributions from the Anoia River were small in the months when the deficits occurred and the LRB cannot be regulated in the lower reaches. However, the effects on the water quality in the lower reaches of the river were not well pronounced, which was due to the small proportion of the Anoia streamflows relative to

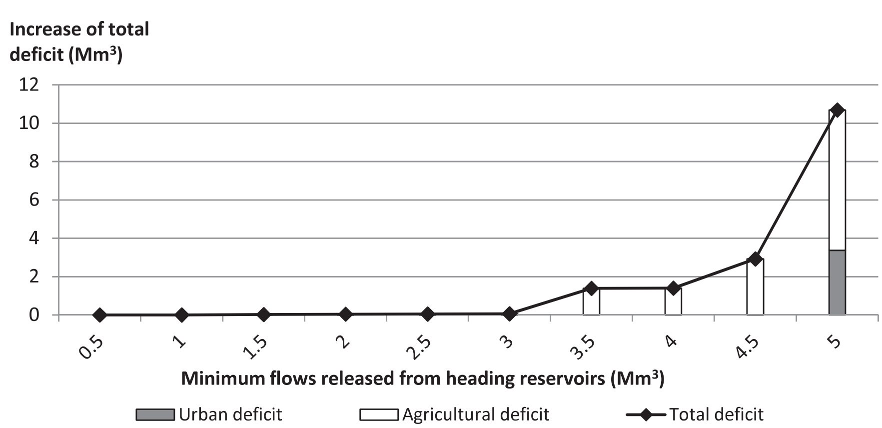

Fig. 7. Increase in the total supply deficit in the drought period by forcing minimum flows in the heading reservoirs. The grey and white bars represent the portion of the total deficit that corresponds to the supply for urban and agricultural demands, respectively.

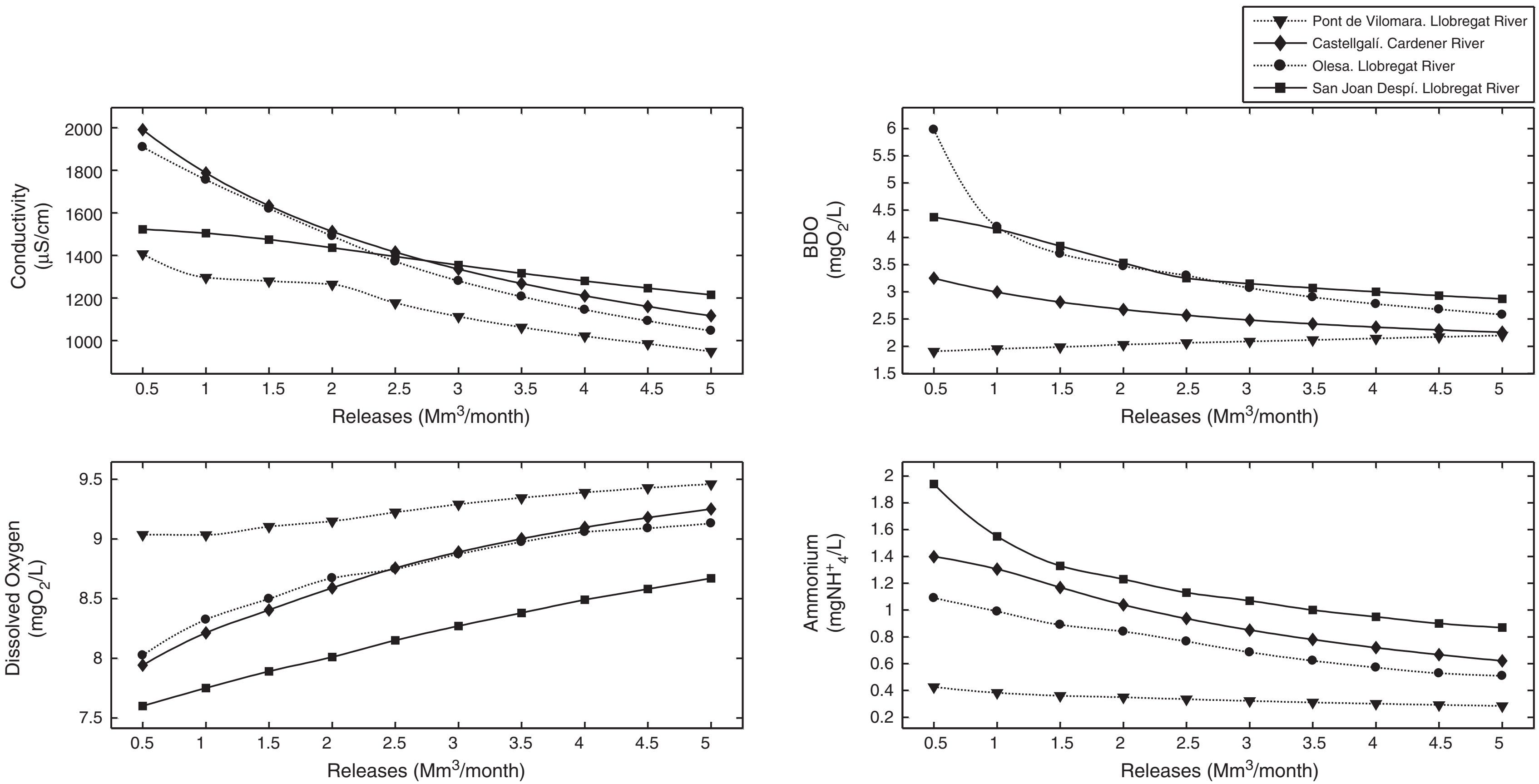

Fig. 8. Evolution of the average pollutant concentrations for minimum flow forcings from the heading reservoirs.

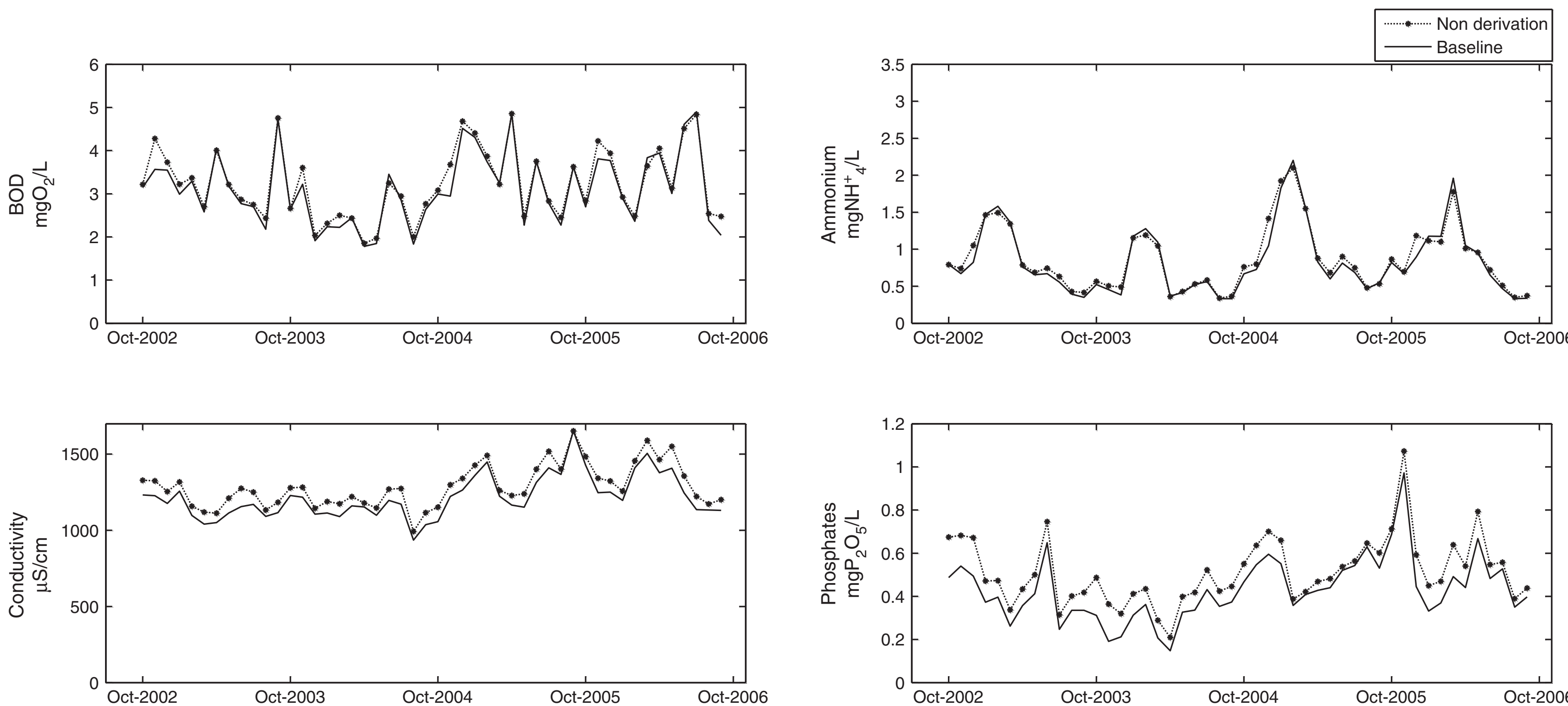

Fig. 9. Evolution of the pollutant concentrations at Sant Joan Despí. Comparison of diverting and non-diverting scenarios for the Anoia River.

the Llobregat River. In general, the results showed a very slight variation in the pollutant concentrations (see Fig. 9). Conductivity was the most affected target variable, increasing by an average of 6%, followed by the ammonium and BOD concentrations, which increased by approximately 5%. The dissolved oxygen concentration exhibited a slight reduction, i.e., less than the 1%. Moreover, the phosphate concentration was the most affected variable among the simulated pollutants. In this scenario, the average concentrations increased by 18%, i.e., from 0.43 to 0.51 mgP_2O_5/L.

This measure is technically easy to apply because it consists of removing a diversion weir. Moreover, this measure causes the melioration of water availability in the lower reaches of the LRB while improving the river connectivity. However, the added difficulty in the elimination of phosphorous in the WWTPs, which is due to the increase in the phosphate concentrations, should be further analysed to make an educated decision.

3.3.3. Improvements in wastewater treatments

Provided that the main problem in the LRB is the water quality in the middle to lower reaches, i.e., where the intakes of the largest WPPs are located, we defined a long-term measure that focuses on improving the WWTPs. In this scenario, many simulations were performed by considering individual improvements to the WWTPs at Manresa, Castellbell, Monistrol, Abrera, and Martorell. Another simulation, which we called the "optimal" scenario, assumed the simultaneous improvement of all WWTPs. Both the treatment of nitrogen and phosphorous were included in the simulated improvements. Actually, reductions in BOD and nitrogen are included in all of the aforementioned WWTPs except for Monistrol. Nevertheless, the implemented measures were not 100% efficient in winter (with low temperatures and scarce nitrification); the ammonium concentrations reached 30 mgNH_4^+/L in some effluents. Moreover, none of the WWTPs specifically removed phosphorous.

We established that the improved discharges had concentrations of 1.5 mgNH_4^+/L, 35 mgNO_3^-/L and 3.4 mgP_2O_5/L (1 mgTotalP/L). Finally, for the Monistrol WWTP, we considered that organic matter was also treated for a final discharge concentration of 20 mgO_2/L of BOD. Table 2 provides a summary of the results from the conducted simulations at the two sites nearest the largest WPPs.

From the simulations in which the WWTPs were individual improved, the main conclusion was the large effect of the improvements at the Manresa WWTP. Specifically, reducing nitrogen and phosphorous in the effluent from this site had a large effect on both the average and maximum concentrations near the mouth of the Cardener River and in the middle and lower reaches of the Llobregat River. At Olesa, the peak ammonium concentrations decreased by approximately 55%, representing a concentration reduction of 1 mgNH_4^+/L with respect to the baseline scenario. A similar reduction was observed in the peak phosphate concentration at the same site. The effects at Sant Joan Despí, while smaller than the effects at Olesa, were also substantial. Several other aspects were notable. For example, the phosphorous concentrations improved at Sant Joan Despí when the treatments were simulated at both the Abrera and Martorell WWTPs. Finally, the results of the optimal scenario revealed that the amount of nutrients provided in the urban water supply intakes could be reduced by 30 to 63%.

According to the results, this type of measure is worth pursuing because it is focused on the source of the problem. By reducing the nutrient concentrations in the lower reaches of the LRB, the WPPs can apply easier and cheaper treatments while simultaneously improving the environmental quality of the river.

3.4. Analysis of the results and decision making

The performed simulations covered a wide variety of measures, i.e., both short- and long-term approaches, for improving water quantity and quality management. The first approach represented a water management alternative that established minimum flows downstream of the heading reservoirs. This action measure considered in isolation would not entirely solve the water quality problems in the LRB because the average ammonium concentrations in the lower reaches of the Llobregat River would remain at or above 1 mgNH_4^+/L. Moreover, the reliability in the supply to the irrigation demands considerably worsens with this approach, which further aggravates the problem.

The second scenario also focused on water management because it suggested a diversion of the Anoia River to the Llobregat River. In this case, the results indicated that water quality would be reduced in the lower reaches of the Llobregat River by not diverting the Anoia River; however, the reduction was not critical. Simultaneously, the increase in available water resources would not provide the expected reduction in the supply deficits to address water scarcity problems.

The last action measure was only focused on long-term water quality improvements by improving different WWTPs. The best results appeared in the optimal simulation. However, based on the efficacy of the investments, any action should be combined with improvements in the treatments applied at the Manresa WWTP. Thereafter, investments focused on improving both the Monistrol and the Abrera WWTPs are warranted.

Table 3 summarises the effects of each measure on the target variables at Sant Joan Despí. The results are very different depending on the type of measure. Reservoir management primarily affected water availability and improved both the BOD and dissolved oxygen concentrations; the incorporation of the flow from the Anoia tributary worsened the water quality of the entire basin while reducing the supply deficits. Moreover, the improvements to the Manresa WWTP largely reduced the nutrient concentrations. The best solution is likely a combination of these measures applied with different proportions depending on the evolution of the drought event and the state of the water resource system. For example, investing in the WWTPs at Manresa and Abrera would reduce the pollution in the lower reaches of the Llobregat River. It would then be more feasible to revert the flow of the Anoia

Table 2
Summary of the water quality results for the wastewater treatment improvement scenarios and nutrients reduction with respect to the baseline scenario.

			Concentrations (mgNH_4^+/L or mgP_2O_5/L)							Percentage of reduction (%)					
			BASE	MAN	CAS	MO	AB	MA	OPT	MAN	CAS	MO	AB	MA	OPT
Olesa	Ammonium	Average	0.63	0.41	0.61	0.58	0.63	0.63	0.33	35	4	8	0	0	47
		Maximum	1.84	0.83	1.78	1.81	1.84	1.84	0.83	55	3	2	0	0	55
	Phosphates	Average	0.4	0.27	0.37	0.37	0.4	0.4	0.21	32	6	7	0	0	46
		Maximum	0.84	0.42	0.83	0.79	0.84	0.84	0.35	50	0	5	0	0	58
Sant Joan Despí	Ammonium	Average	0.92	0.78	0.91	0.89	0.88	0.88	0.65	16	1	3	4	5	30
		Maximum	3.03	2.45	3	3.04	2.97	2.84	2.18	19	1	0	2	6	28
	Phosphates	Average	0.43	0.36	0.42	0.41	0.39	0.37	0.24	16	3	4	9	13	45
		Maximum	0.97	0.91	0.95	0.95	0.67	0.92	0.36	7	3	2	31	5	63

BASE: Baseline scenario; MAN: Manresa WWTP; AB: Abrera WWTP; CAS: Castellbell WWTP; MA: Martorell WWTP; MO: Monistrol WWTP; OPTDEP: Optimal depuration.

Table 3
Summary of the variation of the target variables at Sant Joan Despí with respect to the baseline situation for the different simulated scenarios.

	Variation with respect to the baseline situation				
	% total deficit	% BOD	% dissolved oxygen	% ammonium	% conductivity
Reservoirs management[a]	+13.86	−9.46	+6.64	−5.43	−2.23
Non deviation of the Anoia River	−1.75	+4.93	−0.77	+5.35	+5.81
Improvements in WWTPs [b]	0.00	−0.60	+2.03	−15.69	0.00

[a] Simulation corresponding to 5 Mm^3/month releases from the heading reservoirs.
[b] Simulation corresponding to improvements in the Manresa WWTP.

River and increase the available water resources. The releases from the heading reservoirs could be used as an emergency measure to alleviate specific pollution peaks.

4. Conclusions

The presented study provided an analysis of the pressures that affected the proper operation of the LRB under the drought that occurred from 2004 to 2008. Water scarcity and reduced water quality were part of the main human supply and environmental problems. Several measures were examined as possible short- or long-term solutions, including water management and water quality alternatives. The results showed that water management has a large effect on the water quality state, which in turn determines the suitability of water for the diverse uses in the river basin. This finding highlights the relevance of incorporating water quality into the planning and management of water resource systems that people rely on.

A water allocation model coupled with a mechanistic water quality model was used to address the aforementioned issues. The predictive capabilities of this type of integrated model allow for the testing of many alternatives without actually implementing them. Combined with the development and fulfilment of a methodology adapted to the analysed case, this approach generates useful indicators to support decisions for confronting drought situations from several aspects, which can help us learn from past experiences and define operation rules, series of measures or protocols that improve the functionality water resource systems during future droughts.

Decision support system shells, such as AQUATOOL, facilitate the construction of integrated models for nearly any water resource system. Thus, the presented study could be easily applied to other river basins, which would require appropriate datasets for the calibration and simulation of the integrated model and suitably selected indicators for the analysis. Finally, the compilation and representation of the indicators in a simple and clear manner would make them more useful in the decision-making process.

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Appendix A. Dataset acquisition

The Catalan Water Agency owns a network of permanent gauging stations that collect streamflow data from main rivers. The gauging stations consist of a weir that constrains the cross-sectional area to a predefined value to ensure that highly accurate measurements are collected. The stations measure the water level in the weir section every 5 min; this information is processed to determine the daily streamflow using a rating curve. Then, the daily flows are accumulated to monthly values.

The water quality data used in the present study were collected through a monitoring program approved by the Catalan Government. The concentrations of the different compounds were measured once a month and were analysed in the laboratories of the Catalan Water Agency using suitable standard protocols (accredited procedure by ISO 9001) for each component.

Calibration information

Calibration process

The calibration was conducted from upstream to downstream. The constants associated to the water quality processes modelled were modified inside ranges contrasted by some authors (Bowie et al., 1984; Thomann and Mueller, 1987; Chapra, 1997). First, the values were manually modified inside the ranges with a trial–error process. The adjustment between the observed and predicted values was visually assessed using graphics. In a second part of the calibration process, we used the SCEUA algorithm to look for the best combination of the parameters values, using as start point the resulting values from the manual calibration. In this case the optimisation process was based on the minimisation of the following target function:

$$F = \sum w_X \cdot MSE_X$$

where MSE_X is the mean squared error and w_X is the weight associated to the constituent X. The weights were selected according the relevance of each constituent to the global state of water quality in the basin. Table 4 presents the selected figures for these weights.

Detailed plots of water quality calibration

Figs. 10–15 show the observed and predicted time series of pollutants concentrations at selected water quality stations of the Llobregat River Basin.

Table 4
Weights used in the target function for the automatic calibration process.

Constituent	Weight
Conductivity	5
Dissolved oxygen	4
Ammonium	3
Nitrates	3
BOD	2
Phosphates	1

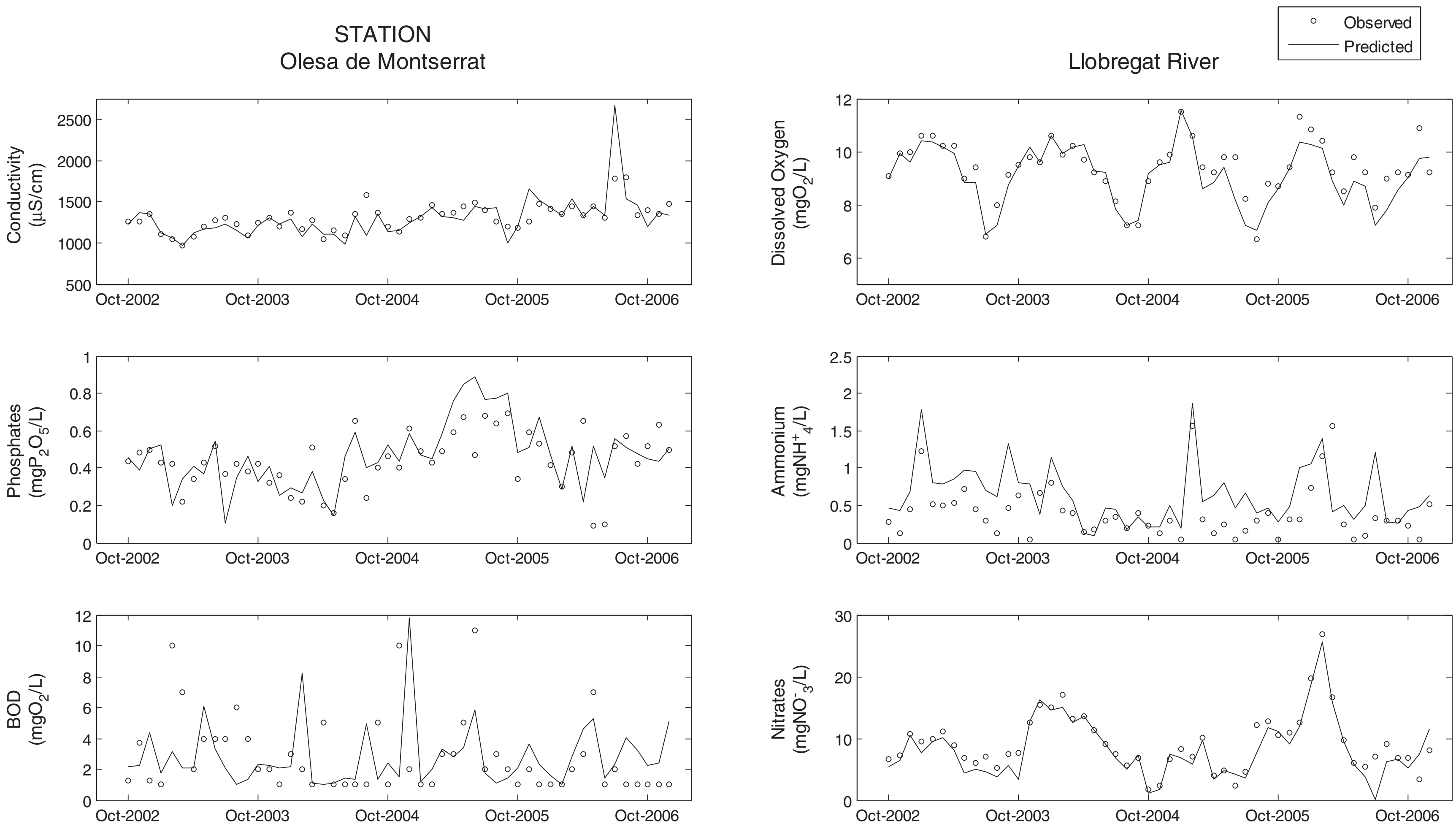

Fig. 10. Detailed calibration plots for the water quality model at Olesa de Montserrat.

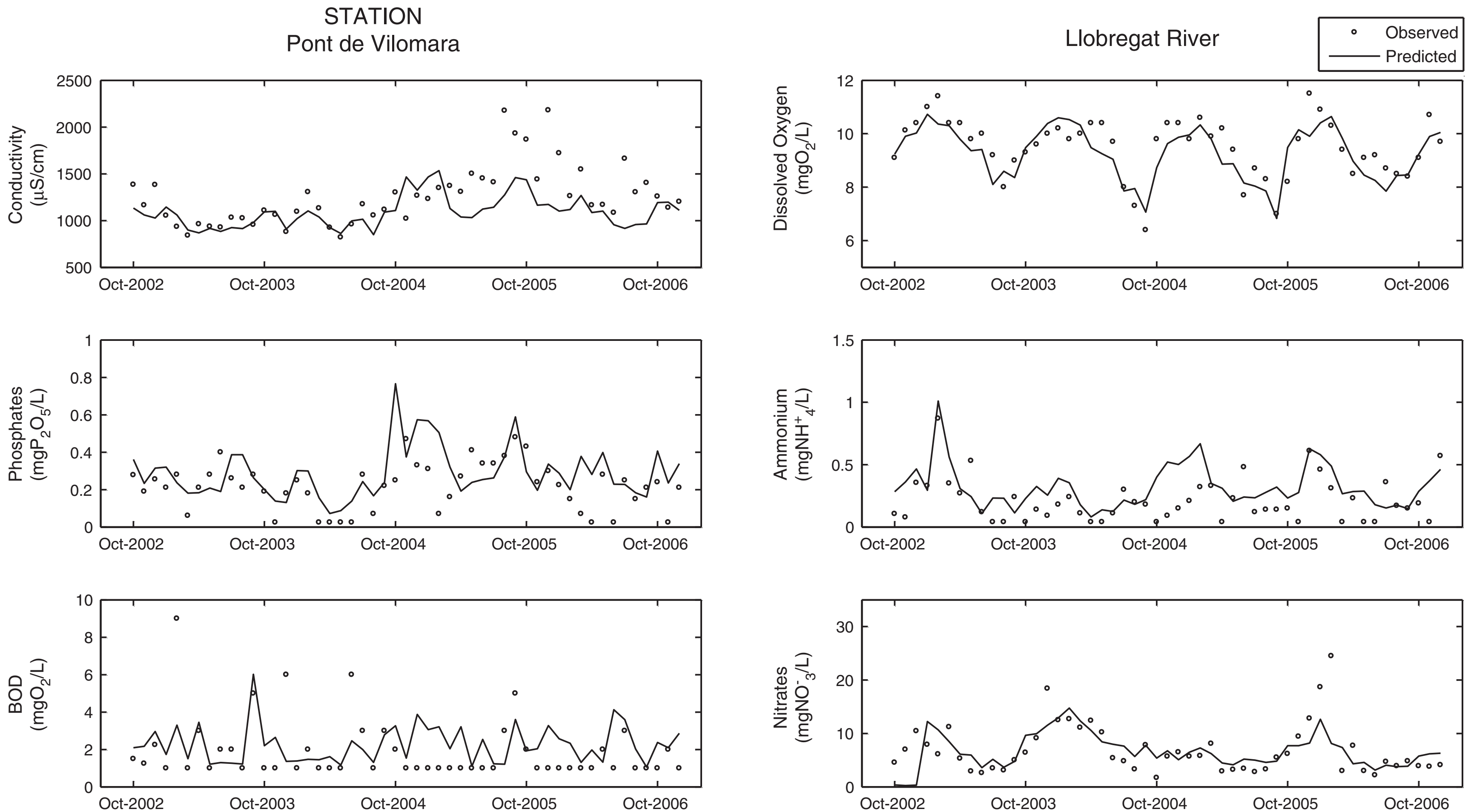

Fig. 11. Detailed calibration plots for the water quality model at Pont de Vilomara.

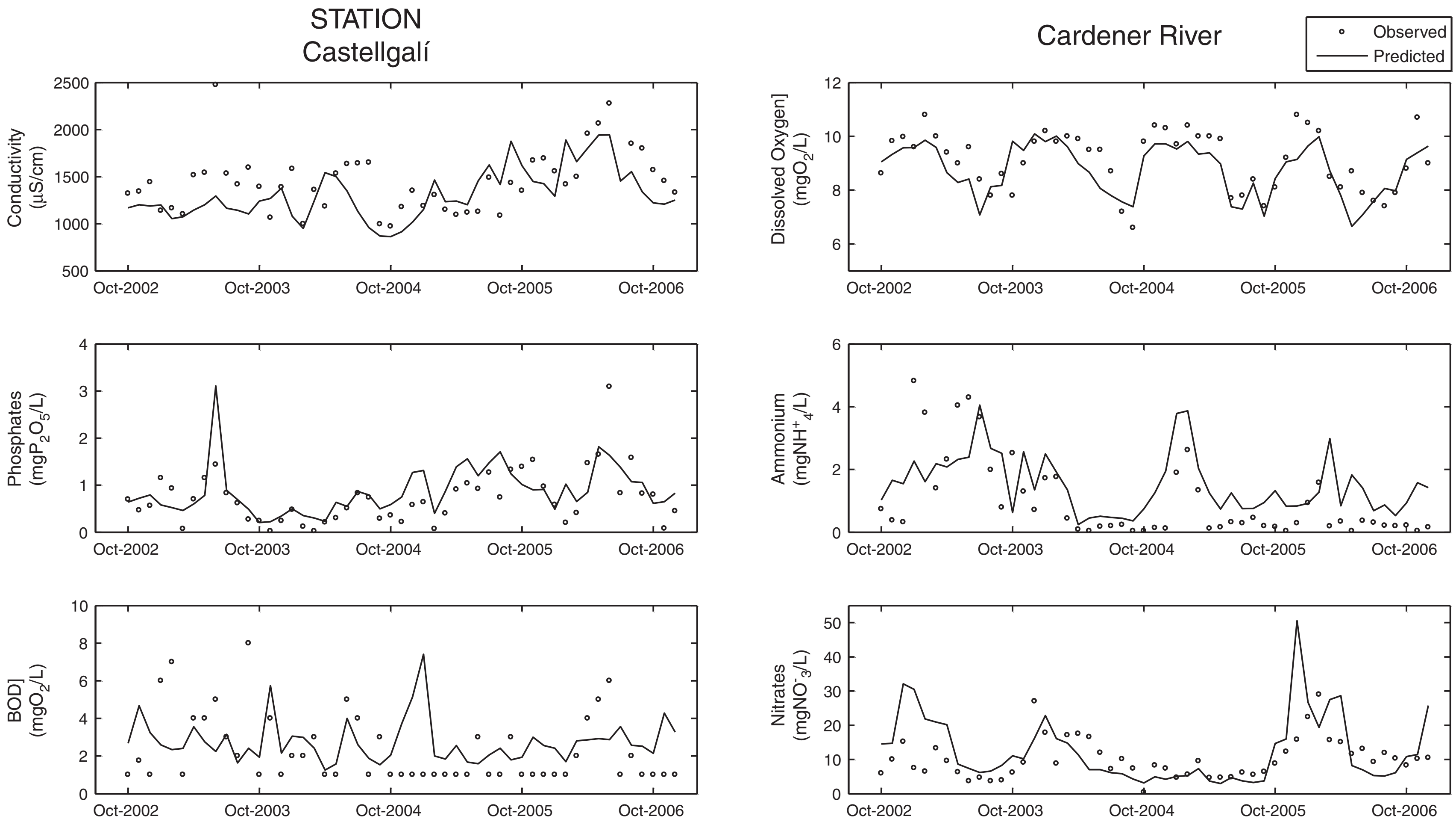

Fig. 12. Detailed calibration plots for the water quality model at Castellgalí.

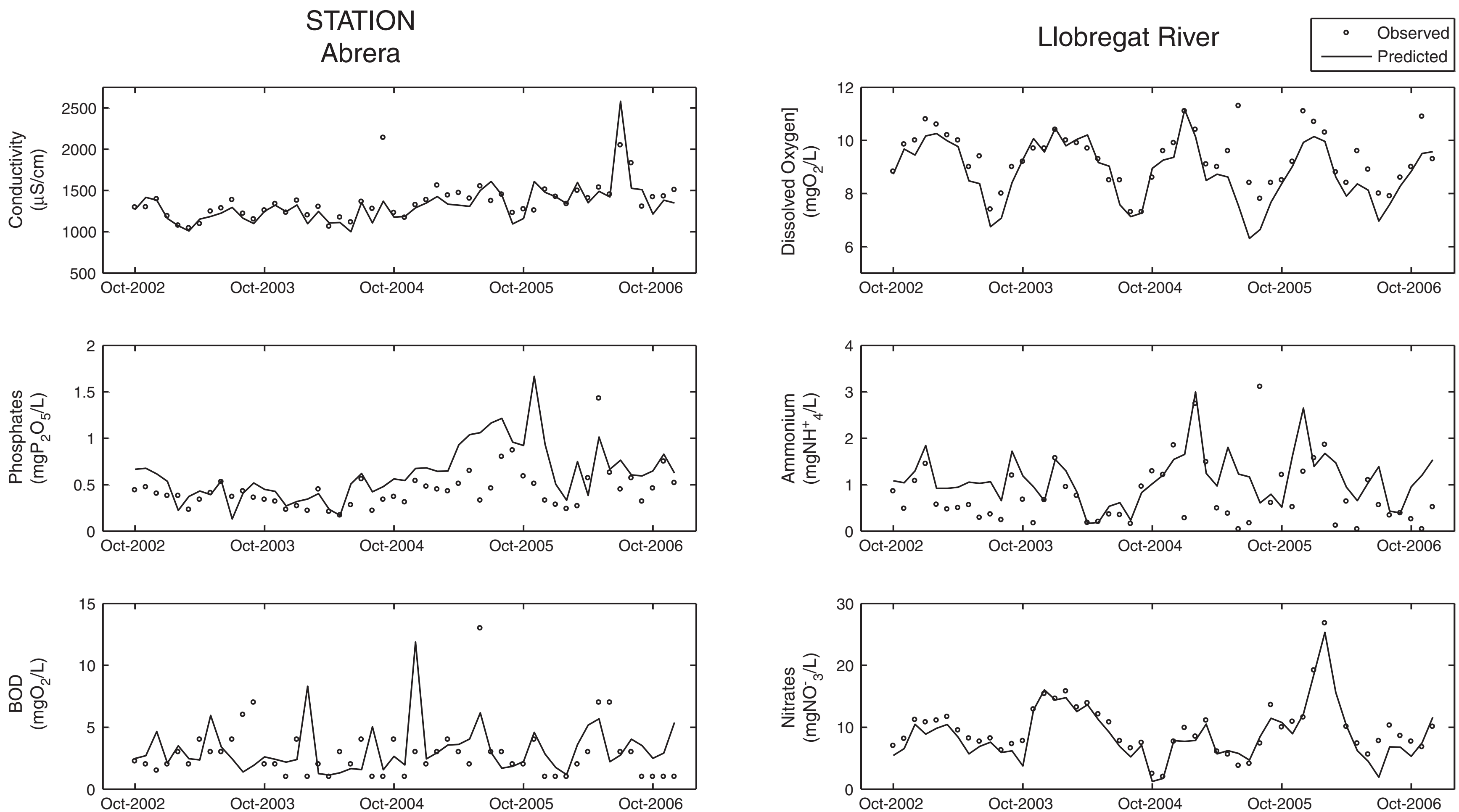

Fig. 13. Detailed calibration plots for the water quality model at Abrera.

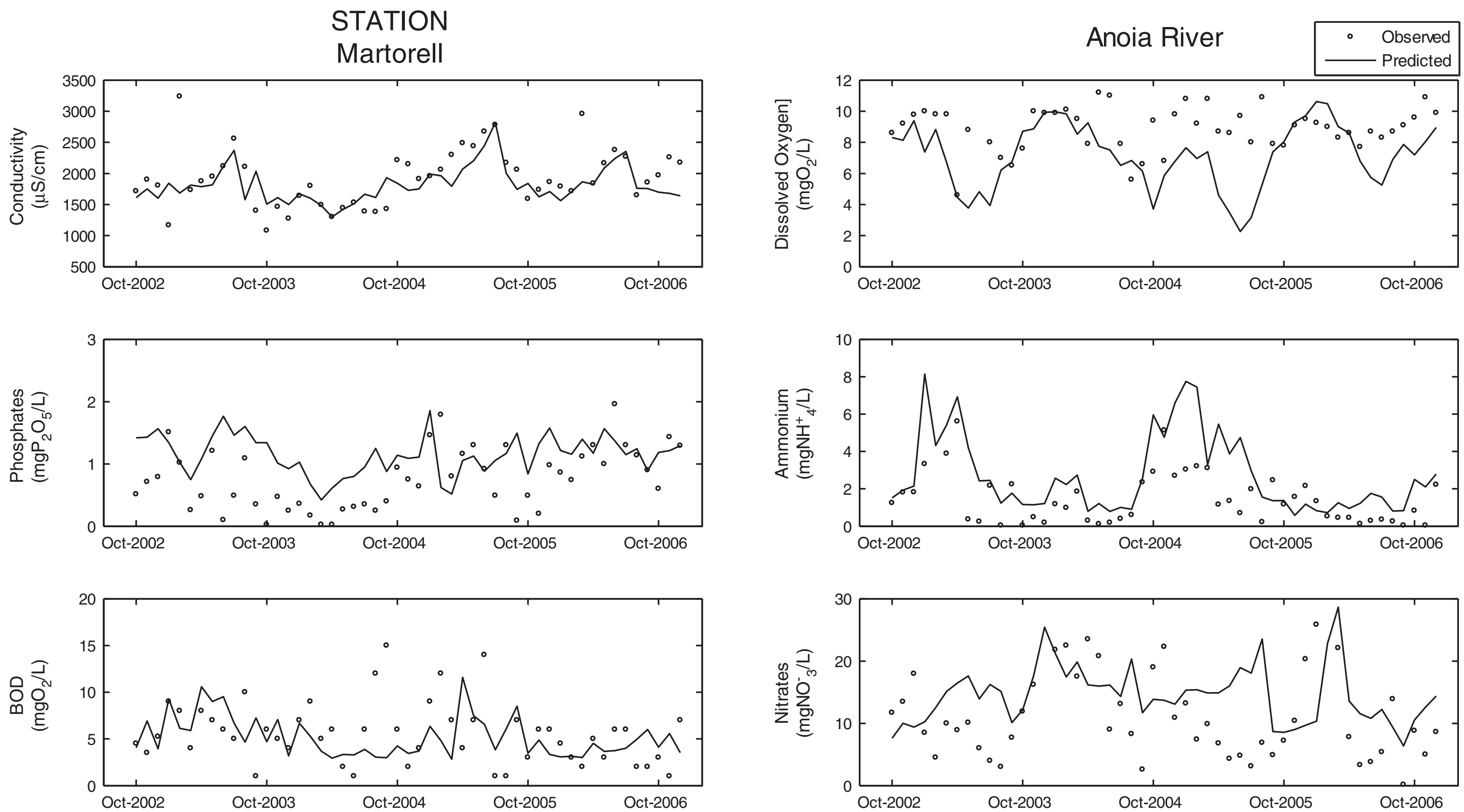

Fig. 14. Detailed calibration plots for the water quality model at Martorell.

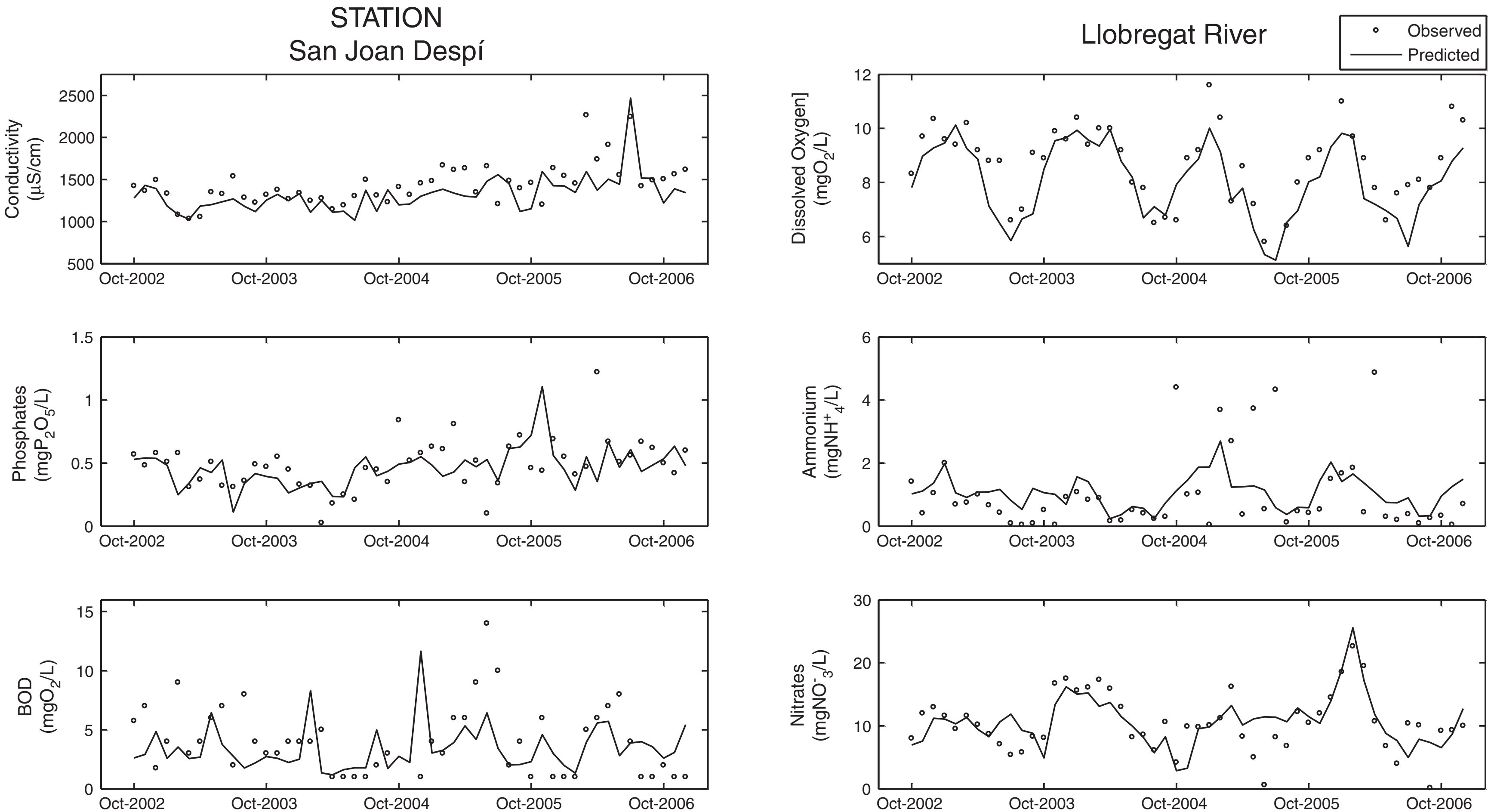

Fig. 15. Detailed calibration plots for the water quality model at Sant Joan Despí.

Table 5
Parameters and ranges resulting from the calibration process.

	Range of values implemented in the model			
	Upper Llobregat River	Cardener River	Middle-Lower Llobregat River	Anoia River
Rate coefficient of reaeration (day^{-1})	0.100–1.500	0.100–1.500	0.100–0.900	1.000–10.000
Rate coefficient of BOD breakdown (day^{-1})	0.020–0.075	0.050–0.075	0.010–0.020	0.010–0.070
Sedimentation rate of BOD ($m\ day^{-1}$)	0.010	0.010	0.010	0.010
Rate coefficient of organic nitrogen breakdown (day^{-1})	0.020	0.020	0.020	0.010–0.020
Sedimentation rate of organic nitrogen ($m\ day^{-1}$)	0.001	0.001	0.001	0.001
Half saturation constant for nitrification (day^{-1})	0.010–3.000	0.300–1.100	0.010–1.000	0.100–3.000
Sedimentation rate of phosphates ($m\ day^{-1}$)	0.000	0.050–0.300	0.000–0.300	0.100–0.250

Upper Llobregat River: From the heading of the Llobregat River to the confluence with the Cardener River.
Middle–Lower Llobregat River: From the confluence with the Cardener River to the mouth of the Llobregat River.

Parameters of the water quality model

Table 5 presents the parameters considered in the water quality model and their ranges of variation resulting from the calibration process.

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