

# Recent changes (1973–2014 versus 1903–1972) in the flow regime of the Lower Paraná River and current fluvial pollution warnings in its Delta Biosphere Reserve

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**Abstract** Alterations in flow regimes of large rivers may originate or increase risks to ecosystems and humans. The Paraná River basin (South America) undergoes human pressures (e.g., heavy damming in the upper basin, deforestation, and mixed pollution) that may affect the water quantity and quality of its terminal Delta (Argentina). In this study, after applying univariate and multivariate change-point detection and trend analyses to the daily data series of flows incoming to the Delta (Paraná-Santa Fe section), flow characteristics were compared by Indicators of Hydrologic Alteration (IHA) and Environmental Flow Components (EFC). Some flood characteristics were also compared from hydrometric levels in the middle Delta (San Pedro station). Chemical and microbiological water variables in the main rivers of the

“Paraná Delta” Biosphere Reserve were examined during two extreme hydrologic years (October 2008 to July 2010) to detect potential risk factors in association with hydrologic conditions. In the Lower Paraná River, a historical period (1903–1972) and two more altered periods (1973–1999 wet period and 2000–2014 dry period) were identified. Flow duration curves evidenced different changes in both altered periods, reflecting the joint effect of climatic variability and human influence. The most evident alterations in the flow regime were the lack of record of the extreme-low-flow component, the attenuation of monthly flow seasonality, and the increase in the number of reversals (dry period) and in the variability of maximum and minimum flow dates. These alterations are consistent with the monthly and daily flow regulation by upstream dams evidenced by available data from the current dry period. In the middle Delta, the marked monthly seasonality in flood days decreased only in the wet period. The proportion between the number of flood days exceeding the evacuation level and that of those exceeding the warning level doubled in the wet period but decreased only slightly in the dry period. In the Delta Reserve rivers, concentrations of *Escherichia coli*, cadmium, lead, iron, manganese, and ammonium exceeded guideline levels under a severe drought and a dispersal of cyanobacteria appeared under a high-flow pulse in La Niña year. The ammonium concentration exceeded the level for human drink with the overbanking flood stage in El Niño year. These occasional detections pose a potential risk to the aquatic life and, especially, to the inhabitants of the Reserve. Flow duration curves, IHA, and EFC are useful tools to evaluate trends or changes of ecological and social relevance in flow regime characteristics.

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## Introduction

The natural flow regime of a river, which comprises five key components — magnitude, duration, timing, frequency, and rate of change—, regulates the chemical, physical, and biological conditions that sustain biodiversity as well as ecosystem integrity and services (e.g., Richter et al. 1996; Poff et al. 1997). Large rivers worldwide have experienced dramatic changes in flow, reducing their natural ability to adjust to and absorb disturbances. Expected changes in global climate and water needs may create serious problems, including risks to ecosystems and humans from increased flooding or water shortages (Palmer et al. 2008). Increasing water problems will mainly affect people whose subsistence depends more directly on the goods and services provided by local ecosystems. This scenario appears more challenging in large rivers, where the interests of upstream stakeholders differ from the interests of those downstream, especially in transboundary basins (Capaldo et al. 2013; Arias et al. 2014).

The Indicators of Hydrologic Alteration (IHA) (Richter et al. 1996) represent the above-mentioned major components of the flow regime (Olden and Poff 2003) and may provide a first approximation of the relative ecological risk to aquatic ecosystems posed by their alteration. The simplest application of the IHA is the comparison of two periods (pre- and post-impact) in a natural river impacted by an event, such as the building of a large dam. However, the decision to analyze trends or contrasting periods is more difficult in the case of rivers with combined impact of increasing human activities (e.g., operation of dams and land-use changes) and climate variability. The more recent definition of the Environmental Flow Components (EFC; extreme-low flows, low flows, high-flow pulses, small floods, and large floods), which are considered as ecologically important in a broad spectrum of hydroclimatic regions, allows the characterization of flow conditions that may be more easily translated into environmental flow recommendations (Mathews and Richter 2007). Nowadays, the environmental flow paradigm has become a major issue for integrated water resource management, within the broader scope of ecological sustainability. Chen et al. (2013) claim that water quality should be considered linked to water flow. These two water issues have been included in the environmental flow definition of the Brisbane Declaration (2007, in Arthington et al. 2010, App. 1).

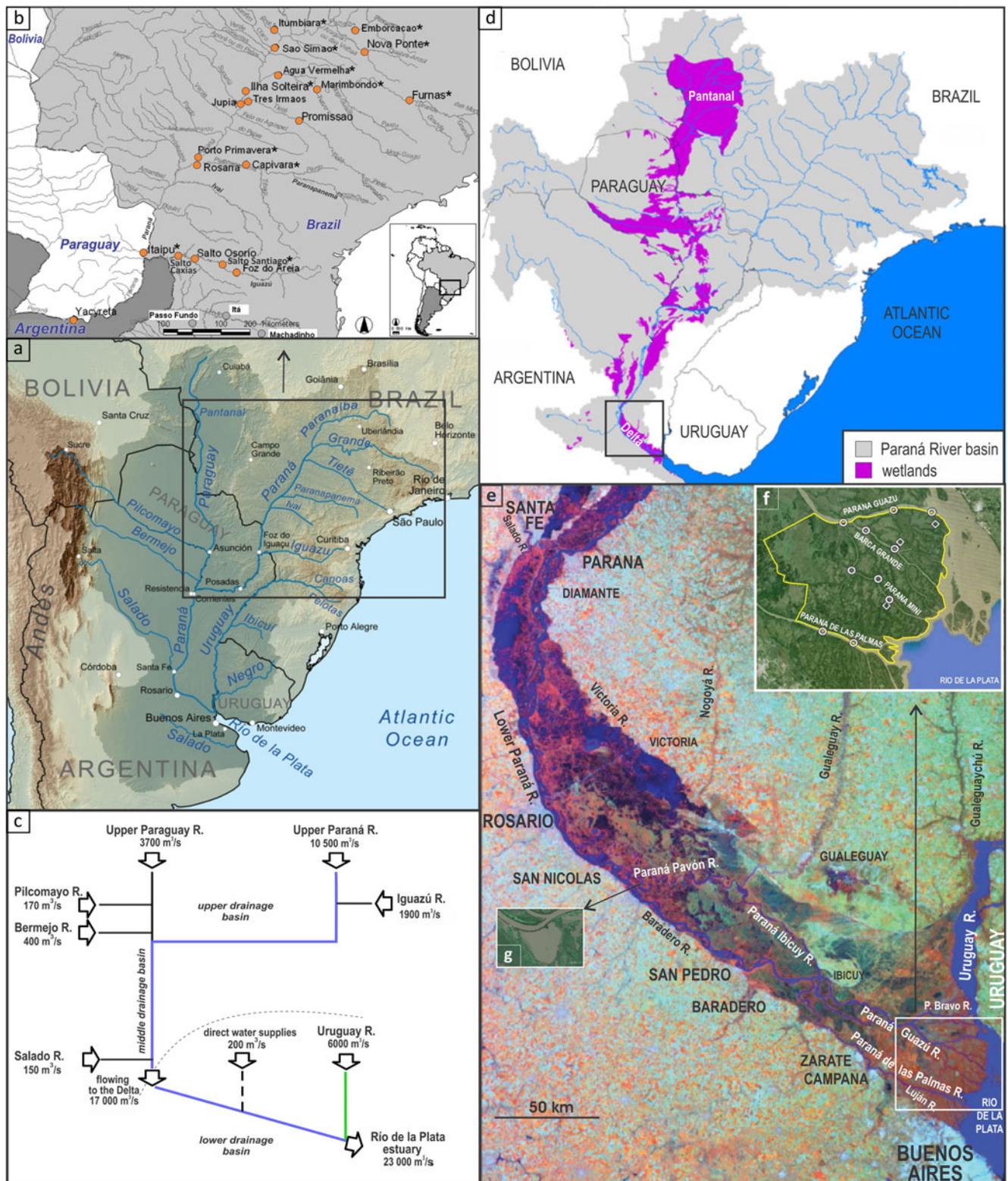
The Paraná River, the second largest river in South America and one of the ten rivers with the highest flow in the world, contributes to most of the water discharged by the La Plata Basin, the second largest drainage basin in South America (Fig. 1a, c). The north–south elongated Paraná basin (2,600,000 km<sup>2</sup>; Fig. 1d) shows a high heterogeneity, embracing tropical to temperate climate zones, a strong east–west precipitation gradient, and a variety of landscapes. This river denotes a relevant axis of biodiversity, population, and

productive activities. The Paraguay–Paraná sub-system represents a key fluvial corridor of functional connectivity from the Pantanal to the Paraná Delta (e.g., Neiff et al. 2005) (Fig. d). In contrast, the Upper Paraná sub-basin has the largest hydroelectric potential in operation in South America (Stevaux et al. 2009). Upstream dams (Fig. 1c) have produced an increase in the minimum water levels, an expansion in the timing of floods, and a marked decrease in the amplitude of the flood pulse in the Middle Paraná River (Quirós 2003).

Previous studies on the Paraná River flow downstream of its confluence with the Paraguay River have focused mainly on the annual to multidecadal variability in its magnitude, considering a general trend or oscillations associated with coupled ocean–atmosphere modes or with sun influence (e.g., Camilloni and Barros 2003; Pasquini and Depetris 2007; Labat 2008; Mauas et al. 2011; Compagnucci et al. 2013; Antico et al. 2014). These studies have shown that the Paraná River flow evidences variability at multiple scales. For example, a recent analysis detected annual and intra-annual oscillations, reflecting the rainfall seasonality of different Paraná Basin sectors, and interannual to interdecadal changes, linked to climate cycles like El Niño/Southern Oscillation (ENSO), the North Atlantic Oscillation, and the Interdecadal Pacific Oscillation (Antico et al. 2014). At large scale, the ~30-year interdecadal oscillation found for the Paraná River (e.g., Labat 2008) was considered as highly significant throughout the entire century (Compagnucci et al. 2013). Likewise, an irregular variability mode of 25–90 years, which appears to be related to the Interdecadal Pacific Oscillation, was detected with remarkable concordance after 1970 (Antico et al. 2014). Many studies have pointed out the increase in rainfalls and flows of the Paraná River after the early 1970s (e.g., Pasquini and Depetris 2007). After this major change, extraordinary floods causing severe damages have been more frequently recorded during a relatively wet period (e.g., Barros et al. 2015). However, after the beginning of the current century, a decrease in the Paraná River flows has been observed (Barros et al. 2015).

The complementary approach of the present study focuses on the changes at large temporal scale in all the components of the flow regime by the estimation of IHA and EFC parameters from daily data, i.e., at an appropriate temporal resolution for most ecological responses (Poff et al. 2010), along more than one century.

Within the Lower Paraná River (Fig. 1e), a fluvio-deltaic complex (17,500 km<sup>2</sup>) extends into the Río de la Plata estuary. In this Delta, changes in water quantity and quality due to different drivers may converge. However, long-term baseline data on deltaic watercourses, which are required to analyze large-scale trends or changes in water quality, are still lacking. In 2000, an island sector (890 km<sup>2</sup>) of the lower Delta was designated as the “Paraná Delta” Biosphere Reserve (MaB-UNESCO Program) (Fig. 1f). The management of this reserve



**Fig. 1** La Plata basin, the Paraná River basin and the Lower Paraná River. **a** Image of the La Plata basin. **b** Some Upper Paraná basin reservoirs (orange circles), distinguishing those with higher useful water volume (>4 km<sup>3</sup>) with an asterisk. **c** Diagram of the main rivers of the La Plata Basin (Uruguay River in green, Paraná River in blue, and Paraná main affluents in black) with their annual flow (mean of each respective historical series). Direct water supplies to the Delta include

watercourses such as the Nogoyá, Gualeguay, Arrecifes, and Areco. **d** Paraná River basin with main watercourses and wetlands. **e** Image of the Lower Paraná River (south of the confluence with the Salado river, near Santa Fe and Paraná cities), including the Delta region (south of Diamante City). **f** Detail of the Delta Reserve with sampling sites in main rivers (circles) and streams (rhombi) during 2008–2010. **g** Detail of the Paraná Pavón River and the adjacent Gorosito Lagoon in the middle Delta

is constrained by the scarce knowledge of the water quality of its watercourses, which support biodiversity and provide ecosystem services, such as water supply for inhabitants (Puig and Olguín 2011). The relatively dry current period of the new century has favored the intensification and diversification of human uses in the Delta (Baigún et al. 2008). In the lower Delta, several studies on fluvial water pollution have been carried out in the first island sector (between the Luján and the Paraná de las Palmas rivers; Fig. 1e) (e.g., Cataldo et al. 2001) or upstream of the Reserve (e.g., Villar et al. 1999). To our knowledge, only our previous study (de Cabo et al. 2003) has been carried out in watercourses of the Biosphere Reserve (between the Paraná de las Palmas and the Paraná Guazú rivers) (Fig. 1e, f). This previous study, which was performed within the relatively wet period, showed an association of fluvial water quality variables with hydrologic stages.

The aims of the present study were (1) to analyze the presence of change points and/or trends and subsequently document changes in the flow regime of the Lower Paraná River by analyzing the series of daily flows incoming to the Delta, (2) to quantify recent changes in the Delta flood characteristics by analyzing the series of daily hydrometric levels in a middle Delta site, and (3) to detect chemical and microbiological signals of water pollution in association with hydrologic phases in a lower Delta sector, by examining variables evaluated in the main rivers of the Biosphere Reserve during two extreme hydrologic years within the current dry period.

To our knowledge, this is the first analysis of the flow regime changes following this approach in the Argentine stretch of the Paraná River. Moreover, the present dry period (so far less analyzed in the literature than the previous wet period) brings the valuable opportunity to disentangle transitory changes likely associated with the particular climatic features of the previous wet period and more persistent changes likely associated with more altered conditions.

## Methods

### Study area

The Paraná River basin drains regions of Brazil, Bolivia, Paraguay, and Argentina. The Middle Paraná begins in the confluence with the Paraguay River (Corrientes city) and the Lower Paraná begins where it receives the Salado River (Santa Fe city) (Fig. 1a, c, e). The Upper Paraná River, which originates in Brazil and receives tributaries mainly from the coastal hills, such as the Iguazú River, contributes to the Lower Paraná with most of its flow (Fig. 1a, c). The rest is mainly contributed by the Paraguay River, which drains the Gran Pantanal (Fig. 1d) as well as the Andean eastern slope through the Bermejo and Pilcomayo rivers (Fig. 1a, c). The northern part of the basin has a well-defined annual cycle with

most intense rainfall during austral summer in the Upper Paraná and Paraguay sub-basins. This rainfall intensification is associated with the seasonal occurrence of the South Atlantic Convergence Zone (SACZ) over this region, a major characteristic of the South American monsoonal system. The central basin region (southern Brazil-northeast Argentina) has a more uniform seasonal distribution of precipitations (Mechoso et al. 2001). The South American Low Level Jet east of the Andes brings moisture from the Amazon basin to this central region of the Paraná basin, especially during the warm rainy season (Vera et al. 2006).

The Pantanal, the largest wetland in the world, plays a key regulation role, smoothing and delaying the arrival of the maximum flow of the Upper Paraguay River in the Lower Paraguay by 4 to 6 months (Hamilton et al. 1996). This delay, which avoids the conjunction of the maximum flow of the Paraná and Paraguay rivers, contributes to the complexity of the annual variability of the Paraná flow downstream of their confluence. Tributaries draining the east-central basin, such as the Iguazú, Ivaí, and Paranapanema rivers (Fig. 1a, b), show flow maxima in summer, winter, and spring (Antico et al. 2014) and contribute to a lesser extent to the annual flow complexity. Usually, in El Niño events, the SACZ tends to move southeastward of Brazil, where the Upper Paraná basin is located, favoring the occurrence of extreme rainfall events (e.g., Valverde and Marengo 2014) and floods in the Paraná River (e.g., Pasquini and Depetris 2007). Conversely, more prolonged dry periods under La Niña events have been suggested (Valverde and Marengo 2014) and normal to low flows in this river have been observed (Pasquini and Depetris 2007). Many studies have revealed that the Pacific Oscillation exerts a modulating effect on ENSO teleconnections over many parts of the world, with significant regional impacts (Wang et al. 2014), for example, in South America (Andreoli and Kayano 2005). El Niño (La Niña) rainfall anomalies tend to be stronger when those episodes occur during the warm (cold) phase of the Pacific Oscillation, but these anomalies weaken or even disappear when both modes are out of phase (Wang et al. 2014).

The Upper Paraná and Paraguay sub-basins have undergone high deforestation due to agriculture and urban expansion mainly from 1950 to 1990. A further change in land cover was the replacement of coffee by intensive soybean production after 1970 (Tucci and Clarke 1998). The industry, mining, and cultivated area have been increasing in the upper basin after the early 1970s (Quirós 2003). Dam construction in the Paraná basin began in 1895 but intensified in 1960–1980 (Stevaux et al. 2009). The Paraná River is the third world's basin by its total number of operational dams for power generation, which currently have a similar proportion of reservoirs and run-of-the-river dams. In general, reservoirs have monthly flow regulation and run-of-the-river dams have daily flow regulation. In the Brazilian portion of the Paraná River

basin, a total volume of 260 km<sup>3</sup> dammed water has been previously estimated (Stevaux et al. 2009). Downstream (~1000 km north of the Delta), the Yacyretá dam (1998, Argentina–Paraguay) has added a total volume of 21 km<sup>3</sup> since 2011 (Yacyretá Binational Entity; [www.eby.org.ar](http://www.eby.org.ar)) (Fig. 1b). Among the several hydropower plants located in the Pantanal catchment, only the Manso dam (2002) has a large reservoir (7.3 km<sup>3</sup>), according to Zeilhofer and de Moura (2009).

The Delta watercourses supply water for consumption and other direct uses of their inhabitants, livestock drinking, fishing and wildlife hunting support, recreation, navigation, etc. Moreover, a water supply plant (named Paraná de las Palmas) has been recently installed to provide drinking water for the continental north suburbs of Buenos Aires City. In the last relatively dry period, there has been a strengthening in cattle raising, afforestation, urbanization, fluvial transport, recreation demand, wood industries, and industrial fishing in the Delta (Baigún et al. 2008).

The upper Delta and the middle Delta have numerous and various shallow lakes and, as a consequence of the flooding of vast areas, evidence an important capacity to soften downstream water pulses. The lower Delta islands (from the Ibicuy islands to the river mouth), relatively higher and with high surrounding natural levees, remain more protected from upstream floods, thus favoring human settlement. In this sector, the water quality depends not only on the different contributions of the main tributaries of the Paraná River but also on processes such as the interaction with the island marshes (Villar et al. 2001; de Cabo et al. 2003). The drainage network of the Reserve is characterized by large rivers ending in deltaic fans, such as the Paraná Guazú and Paraná de las Palmas rivers, and small rivers with a dendritic pattern of distributaries in NW–SE direction. The watercourses of the Reserve, except the Paraná de las Palmas River, are part of the drainage network of distributaries of the Paraná Guazú River (Fig. 1f). More details on the Delta and the Reserve are provided in Puig et al. (2015).

### Sources of hydrologic data

The 1902–2014 series of the Paraná River daily flows at the Paraná–Santa Fe (Fig. 1e) full cross section (i.e., including the main river channel, the Colastiné River, the Setúbal system, and a series of reliefs) was selected for analyses of the flows incoming to the Delta region (~40 km downstream). The 1902–2014 series of hydrometric levels in San Pedro gauge station (0.7 % of missing data), which is located around the middle of the Delta (33° 40' S, 59° 43' W, Fig. 1e), was considered for complementary analyses about several Delta flood characteristics. The daily flow contribution to the estuary by the deltaic fan of the Paraná Guazú River (estimated by hydrologic models) was considered for the water quality

evaluations performed in watercourses of the Delta Biosphere Reserve. All these hydrologic data were provided by the Argentine Water Institute (INA).

The upstream total dam storage capacity measured in number of years of river flow was proposed as an index (named Storatio) of the maximum potential degree of flow alteration (FitzHugh 2014). This index was coarsely estimated for the early 1970s, from useful and total dammed volume in Fig. 5 of Rocha (2010) and the concordant total dammed volume in Fig. 4 of Quirós (2003), and for current available data (2015) from the dammed volume (~70 dams) in the Brazilian Paraná River basin ([www.ons.org.br](http://www.ons.org.br)) and in the Yacyretá dam ([www.eby.org.ar](http://www.eby.org.ar)).

The reconstructed flow values (removing effects of dam regulation, reservoir evaporation, consumptive uses, and water diversions, but not removing effects of land-use changes, such as deforestation, afforestation, and agricultural management) downstream of all the Upper Paraná basin dams, i.e., downstream the Itaipú (Paraná River) and the Salto Caxias (Iguazú River) dams, were obtained from Operador Nacional do Sistema Eléctrico (ONS, Brazil) web site ([www.ons.org.br](http://www.ons.org.br)).

### Change-point detection and trend tests of the Paraná River flow

Change-point detection and trend tests of the Paraná River flow were applied to support the decision on the appropriate application of the IHA. A preliminary estimation of the IHA from the complete daily flow series of the Paraná River at the Paraná–Santa Fe section was carried out considering the hydrologic years for this river (September to August period, named by the second year from this point on) and following a nonparametric approach (based on median and percentiles). Then, the Pettitt's test, a nonparametric test commonly applied to detect a single change-point (abrupt or step change) in univariate hydrologic series with continuous data (Pettitt 1979), was applied to the series of annual (hydrologic year) and monthly median flows. This method was successively applied to each segment resulting from the detection of a significant change-point. The sensitivity of the Pettitt's test increases when the series length is large and represents the central part of the distribution (e.g., mean or median series), when the data variability is low, when the change-point magnitude is high, and when it occurs toward the time series center (Mallakpour and Villarini 2015). The commonly used nonparametric Mann–Kendall test (e.g., Yue et al. 2002) was applied to detect monotonic trends in each resulting segment of the series. Among other recently developed methods for multivariate change-point detection, a nonparametric hierarchical estimation algorithm for multiple change-point analysis and test by permutations (James and Matteson 2014) was selected. This method is robust to the presence of anomalies in data distribution, can detect more than one change point while

considering the complete series analyzed, and is able to detect any type of distributional change within the data. This test was applied to a standardized multivariate series of selected IHA, considering the divisive option (a bisection algorithm sequentially identifies change points) and a minimum segment size of 10 years. The selected IHA variables representing different flow regime characteristics (dates were excluded because their analyses require circular statistics) were as follows: median, 1-day minimum, 1-day maximum, base flow index, rise rate, fall rate, and number of reversals. The Pettitt's and Mann–Kendall's tests were performed using the “trend” package, version 0.0.1 (Pohlert 2015), and the multiple change-point analysis of multivariate data was performed using the “ecp” package, version 2.0.0 (James and Matteson 2014) of the R software, version 3.2.2 (R Core Team 2015).

The flow duration curves (see Appendix) for the significant periods identified in the flow series of the Paraná River, as well as some segments delimited by a first potential nonsignificant change point, were obtained by the IHA software and plotted together in a figure for visual comparison.

### Analyses applied to the periods identified

The periods identified were characterized by estimating the IHA and the EFC (see Appendix) following a nonparametric approach. Default options were applied for large floods (those with a recurrence time of 10 years) and extreme-low flows (10 % percentile of daily flows) for the complete data series. Then, the corresponding flows for these two thresholds were considered as fixed values to perform consistent comparisons between each pair of periods. Other thresholds for the ecological flow components were adapted for this study about the Paraná River considering characteristics relevant for the fluvial water quality, such as the degree of the river–floodplain connection. The threshold between low and high flows was proposed at 18,000 m<sup>3</sup>/s. This preliminary bankfull value assumed for the full cross section considered the bankfull flow determined for the Paraná station in the 1981–1995 period (17,140 m<sup>3</sup>/s; Amsler et al. 2005) and our direct evidence of a river–lagoon connection in the middle Delta (December 10, 2008). The high-flow-pulse component was redefined as flows between the bankfull and the inundation stages, thus representing a range of more or less limited fluvial contact with the floodplain environments. All floods were considered above the inundation threshold, i.e., flow generating overbanking in the Delta islands. This inundation flow (22,500 m<sup>3</sup>/s) was estimated by contrast of the annual maxima of the Paraná station flows and the inundation stage in San Pedro station. The mean value of the frequency of events in each period was recalculated with more precision (two decimal digits instead of none, as provided by the IHA software) from annual values. The degree of change between the median values of the subsequent and the preceding period for each parameter was expressed as a percentage of the preceding value (negative sign indicating

decrease in the subsequent period). The IHA and EFC parameters were computed by the IHA software, version 7.1 (TNC 2011). Dates are expressed as Julian dates (1 = January 1; 60 = February 29; 366 = December 31). Since the date is a periodic variable, the partial correction considering four (IHA software) or eight (FitzHugh 2014) periods of the year does not seem a satisfactory procedure. Therefore, Julian dates were converted to angles expressed in degrees (360 range, instead of 366) and the mean and variance were determined for each date parameter in each period by circular statistics (e.g., Magilligan and Graber 1996). Both circular variables were obtained by the “VecStatGraphs2D” R package (Ruiz-Cuetos et al. 2014). Then, the degree of change in Julian dates was estimated as the number of days between each respective pair of means (reconverted to a 366 range) and expressed as a percentage, considering that a half year (183 days) is the maximum possible difference (100 %) between two dates, as in the formula of the IHA software (TNC 2011).

Nonparametric tests were applied to IHA and EFC values to assess statistical significant changes in their central tendency (Wilcoxon's test) and in their year-to-year variability (Siegel–Tukey's test). The Siegel–Tukey's test was applied after adjusting for differences in median values of each pair of periods compared. The two-tailed version of the Wilcoxon's and Siegel–Tukey's tests was performed using specific functions developed for the R software. The direction (increase or decrease in the subsequent period) of the change in variability was obtained from the Siegel–Tukey's test. Frequencies and dates were not tested.

The seasonality degree of monthly median flows in the Paraná-Santa Fe section and that of monthly flood days in San Pedro gauge station (i.e.,  $\geq 2.4$  m) of each period were quantified by a monthly concentration degree index during the year (CDI, see Appendix), which varies between 0 (even distribution between each month) and 1 (concentration in a specific month) (Ling et al. 2014).

Floods of at least seven uninterrupted days were considered in San Pedro, in concordance with the minimum time usually considered as ecologically relevant (Martínez Santa-María and Fernández Yuste 2010). The degree of change and variability of some characteristics of these floods were tested for each pair of periods identified by the above-mentioned Wilcoxon's and Siegel–Tukey's tests. The number of days exceeding the warning level ( $\sim 3$  m) and the number of days exceeding the evacuation level ( $\sim 3.6$  m) were estimated for each period identified.

### Chemical and microbiological evaluations in the Delta Reserve

Chemical and microbiological data in the Delta Reserve were obtained from surveys carried out by the SPA-1 scientific

vessel through inter-institutional cooperation (Argentine Museum of Natural Sciences, Argentine Coast Guard, and Municipality of San Fernando). Qualitative (20- $\mu\text{m}$ -mesh net) and quantitative (unfiltered and fixed with Lugol) phytoplankton samples from 13 fluvial sites of the Biosphere Reserve (Fig. 1f) in nine samplings (October 2008 to July 2010) were examined under an inverted microscope (Utermöhl 1958) for identification and quantification of cyanobacteria. These organisms were also examined in additional samples (December 2008) from two environments of the middle Delta (Gorosito Lagoon and Paraná Pavón River, Fig. 1g). After the beginning of the second survey, water samples were collected in one site for each of the four main rivers according to standardized protocols and preserved at 4 °C until analyzed (<24 h) in the Central Laboratory of AySA (Argentine Water and Sanitation S. A.), following standard methods (APHA 2005). In particular, the concentrations of some total heavy metals, such as arsenic, cadmium, lead (3113B AA-oven method), iron, and manganese (3120B method), and the fecal bacterium *Escherichia coli* (MPN/100 ml; 9221 method) were determined. More details on these Reserve samplings are provided in Puig et al. (2015).

These chemical and microbiological variables usually related to water pollution were compared with guideline levels for different uses of surface freshwater (aquatic life protection, human drinking, and recreational use). The recreational use includes all human activity involving immersion, ingestion, or contact with water (USEPA 2002). The national regulations considered were: National Law of Dangerous Wastes N° 24,051 (Regulatory Decree N° 831/93 and Resolution 242/93), Argentine Mining Code (Law of Environmental Protection N° 24,585), Argentine Food Code (Article 982, Joint Resolution N° 68/2007 and N° 196/2007), and National Law of Environmental Management Regime of Waters N° 25,688 (recommended values, since law regulation is still pending). The international guideline levels established by WHO (2011) and USEPA (2002) were also considered.

## Results

### Identification of large-scale periods in the Paraná River flow series

The successive application of the single change-point Pettitt's test to the series of medians per hydrologic year allowed detecting a first significant change point in 1972 (last year of the first segment of the series) and a second change point in 1999 (Table 1). A similar application of this test to series of monthly flow medians (Table 1) showed nonsignificant change points from January to April, a significant change point from May to December (with maximum significance in September and a value delayed to 1978 in June and July), and a second

significant change point within the last segment for June (1998) and July (1999). A subsequent potential change point (~1933) in annual and several monthly medians resulted nonsignificant. The application of the Mann–Kendall test to each of these significant annual and monthly segments showed no significant monotonic trend. The hierarchical multiple change-point analysis (99,999 permutations) applied to a group of standardized IHA parameters detected a first change point ( $p=0.00001$ ) in 1973 (first year of the new segment) and a second change point ( $p=0.0002$ ) in 2000, the subsequent potential change point (1983) being nonsignificant ( $p=0.41$ ). Thus, at annual scale, both methods identified a main change between 1972 and 1973 and a secondary change between the 1999 and 2000 hydrologic years.

The estimation of the Storatio index (0.056) from the useful volume (~27 km<sup>3</sup>) for the last hydrologic year (1972) of the historical period and the mean flow for this period was similar to the threshold (0.05) below which the flow alteration is considered as minimal. In contrast, the Storatio index calculated from current data of the upstream useful dammed volume (145 km<sup>3</sup>) and the mean flow for the current dry period was 0.28, thus exceeding the threshold (0.2) that indicates often moderate to high level of flow alteration (FitzHugh 2014). These Storatio index values doubled (0.11 and 0.6, respectively) when the respective total dam storage capacity (~55 and 310 km<sup>3</sup>, respectively) is considered (as in FitzHugh 2014) instead of the useful dammed volume (which reflects the effective regulation capacity). The first segment of the series (1903–1972), which was minimal dam regulated, will be named in this study as “historical” period (i.e., relatively normal period from a hydroclimate standpoint). The two more dam-regulated segments (and more altered in general) will be named according to their respective dominant flow feature, as “wet” (1973–1999) and “dry” (2000–2014) periods.

The detection of flow variability at different scales requiring specific methodologies is beyond the scope of this study. However, the inclusion of some nonsignificant segments in the flow duration curves (Fig. 2a) allowed the visualization of the variability within the historical and the wet periods. The variation within the historical period, e.g., between wetter (1903–1933) and drier conditions (1934–1972), was lower than the changes after the early 1970s, as evidenced by the respective flow duration curves (Fig. 2a). The curve of the dam-regulated wet period in general paralleled the historical one at very higher values and, in particular, the curve of the 1983–1999 segment evidenced the highest values. In the dam-regulated dry period, the curve was similar to the drier historical conditions from higher flows to around 19,000 m<sup>3</sup>/s (~25 % of exceedance probability) but differed progressively by increasing the exceedance probability toward low flows. The curves of the dam-regulated wet and dam-regulated dry periods approached in the final part, decreasing sharply for extreme-low flows (Fig. 2a).

**Table 1** Change-point detection (Pettitt's test) in the monthly and annual flow medians of the Lower Paraná River at the Paraná-Santa Fe section (upstream of the Delta)

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Year
K	2162	1811	1552	1247	819	793	526	306	962	1161	1255	1880	1512
p	5e-09***	2e-06***	7e-05***	0.003**	0.12	0.14	0.62	0.82	0.04*	0.007**	0.003**	6e-07***	0.0001***
Change point	<b>70</b>	<b>70</b>	<b>70</b>	<b>70</b>	<b>70</b>	<b>70</b>	<b>54</b>	<b>101</b>	<b>70</b>	<b>76</b>	<b>76</b>	<b>70</b>	<b>70</b>
<i>Historical</i>	1903-1972 1903-1972 1903-1972 1903-1972												
K	332	325	246	231					267	288	221	206	303
p	0.30	0.32	0.70	0.80					0.58	0.65	0.97	0.96	0.41
Change point	31	31	31	13					64	30	30	59	31
<i>Altered</i>	1973-2014 1973-2014 1973-2014 1973-2014												
K	210	144	116	129					167	201	196	157	255
p	0.06	0.38	0.69	0.54					0.22	0.013*	0.016*	0.28	0.01**
Change point	27	27	27	13					26	<b>20</b>	<b>21</b>	27	<b>27</b>
<i>Wet</i>	1979-1998 1979-1999												
K										36	37		78
p										0.79	0.86		0.33
Change point										14	3		7
<i>Dry</i>	1999-2014 2000-2014												
K										21	38		26
p										0.98	0.18		0.65
Change point										11	10		10
<i>Series segments</i>	1903-1972 1903-1972 1903-1972 1903-2014 1903-2014 1903-2014 1903-1972 1903-1978 1903-1978 1903-1972 1903-1972												
	1973-2014 1973-2014 1973-2014 1973-2014 1973-2014 1973-2014 1979-1998 1979-1999 1973-2014 1973-1999												
	1999-2014 2000-2014												

Hydrologic year (September–August period) named by the second year; change point (order of the last year of the first segment) in bold for significant change \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

## Recent changes in the flow regime of the Lower Paraná River

The mean annual flow in the historical period (15,290 m<sup>3</sup>/s) increased (34 %) in the wet period (20,860 m<sup>3</sup>/s) and decreased in the dry period (16,390 m<sup>3</sup>/s, only 8 % higher than in the historical period).

Considering the results of the tests on IHA and EFC parameters that reached significance, the median flows in all months, except April, increased from the historical period to the wet period (Table 2 and Fig. 2b). This increase, affecting mainly austral late winter and spring seasons, varied from 18 % (March) to 63 % (October). The median flows from August to November (mainly spring) remained higher (26–39 %) in the dry period than in the historical period (Table 2). The year-to-year variability in monthly flows, which increased in September in the wet period, was lower in the dry period than in the historical period in September, October, December, and June (Table 2). The minimum flow for 1 day (Fig. 2c) to 90 days increased (54–62 %) from the historical to the wet period and remained higher (30–50 %) in the dry period than in the historical period (Table 2). The frequency of low pulses decreased radically (>80 %) from the historical to the wet and dry periods. The maximum for 1 day (Fig. 2c) to 90 days, as well as the frequency of high pulses, increased in the wet period (~30 and 59 %, respectively, Table 2). The base flow index (7-day minimum flow/mean annual flow) increased from the historical to the wet period (17 %) and the dry period (26 %). The rise and fall rates increased slightly in the wet period, whereas the number of reversals increased strongly in the dry period (74 %). The most notable change of the EFC (Fig. 3 and Table 2) was the lack of record of extreme-low flows since the beginning of the wet period (the 10 % percentile threshold of daily flows was slightly higher than the historical mean of annual minimum values), despite the predominantly dry feature of the last period. Consequently, a new component (named very low flows) was defined for the altered periods by a new threshold of 10 % percentile of their daily flows (Fig. 3), to allow their comparison with future data. The variability in the peak magnitude of the high-flow-pulse component (bankfull to inundation flows) decreased in the dry period (Table 2). In the wet period, the magnitude and variability of the fall rate of small floods decreased, the frequency of large floods was more than threefold that of the two other periods, and their variability in duration increased (Table 2).

A delay of around 1 month was observed in the peak of small and large floods in the wet period (Table 2). However, the main timing change in both altered periods was the increase in the variability of dates of maximum and minimum flows (Fig. 4).

Considering the kind of changes (Fig. 5) besides its statistical significance, several parameters evidenced a change only

in the wet period (with reversion in the dry period to values similar to those of the historical period), a few changed only in the dry period, several changed in opposite direction in both altered periods (increased in the wet and decreased in the dry with respect to the historical period), but numerous parameters showed a change in the same direction in both altered periods (only partial reversion of the change in the wet period, similar values in both periods, or even an intensification of the change) with respect to the historical period (Fig. 5).

The concentration degree index during the year (CDI) estimated for the monthly median flows in the historical period (0.14), with maximum in March–April (Fig. 2b), decreased more than twofold in the wet period (0.06) and even more in the subsequent dry period (0.05).

## Flood characteristics in the middle Delta

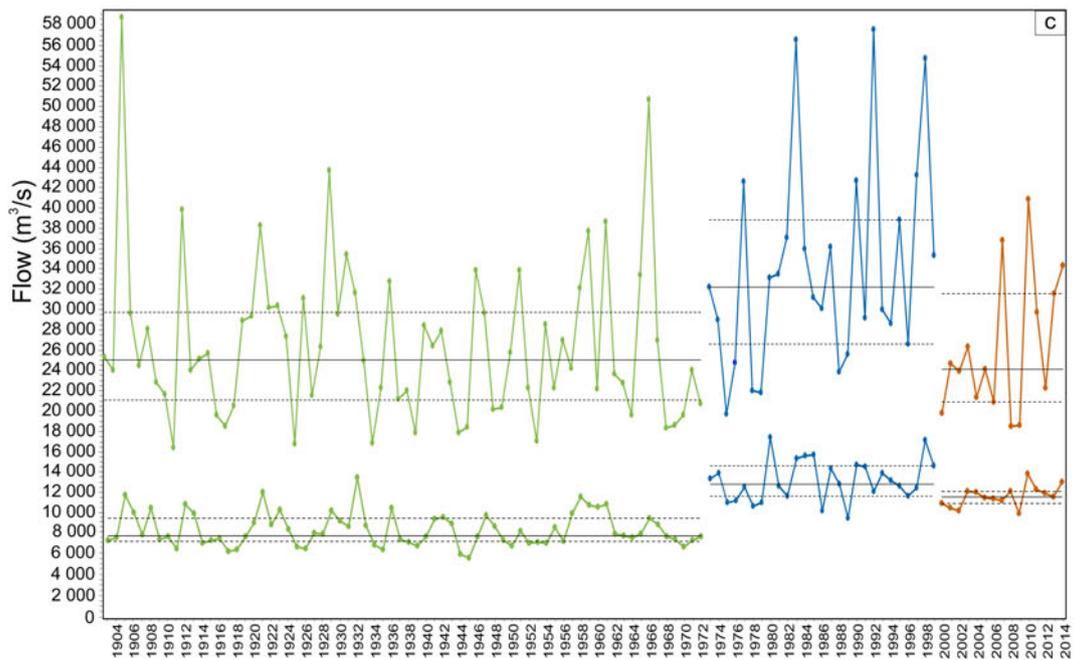
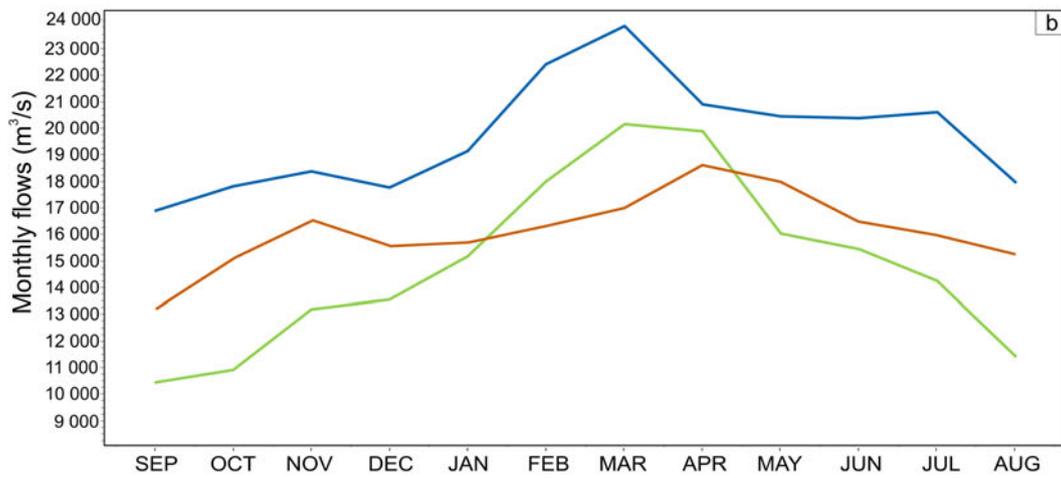
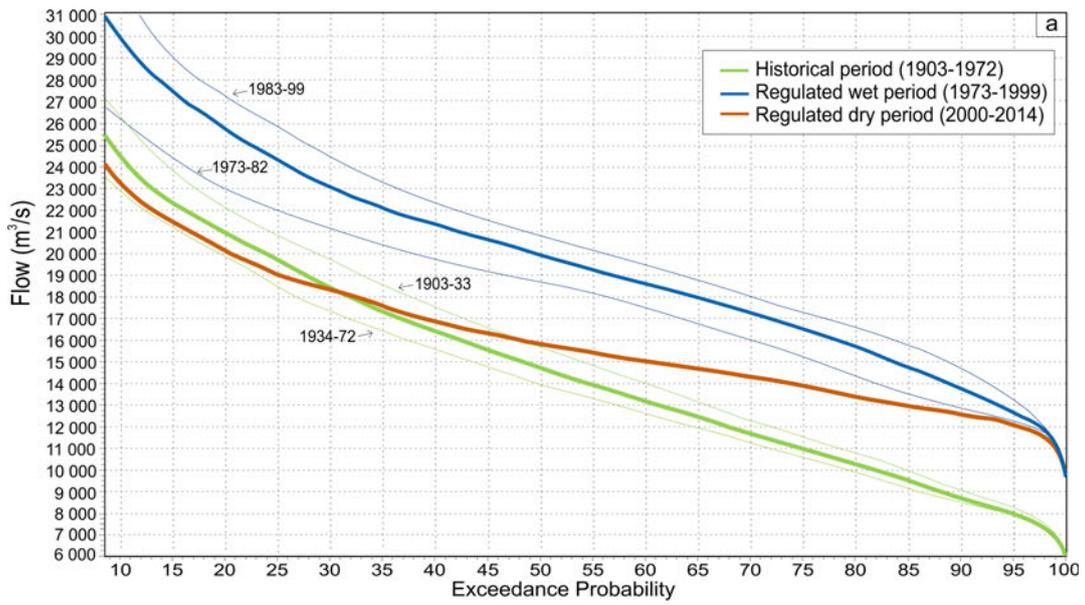
In San Pedro, the CDI showed that the concentration degree in the number of monthly flood days during the year in the historical period (0.51) decreased threefold in the wet period (0.17) but increased in the subsequent dry period (0.48). The number of monthly flood days showed the maximum in May in the historical and the dry periods but showed higher values from March to August in the wet period (Fig. 6).

The number of flood days ( $\geq 7$ ) per hydrologic year (Table 3) was significantly higher (43 %) in the wet period ( $p=0.03$ ) and lower (56 %; nonsignificant) in the dry period than in the historical period. Also, the duration of the maximum uninterrupted flood per hydrologic year was higher in the wet (41 %) and lower in the dry period (34 %) than in the historical period (Table 3). The flood started about 1 month early in the wet period and its maximum level was reached about 1 month early in the dry period (Table 3). The year-to-year variability in the onset flood date doubled in the wet period and was also higher (~50 %) in the dry period than in the historical period, and the variability in the flood maximum date (Fig. 7) increased in both altered periods (~30 and 40 %, respectively) (Table 3). The mean frequency of years without inundation decreased to a quarter in the wet period (Table 3 and Fig. 7).

In San Pedro, the flows exceeding the warning level (~3 m) affect the levees of most of the islands and those exceeding the evacuation level (~3.6 m) include also urban affectation. The ratio between days exceeding the evacuation level and days exceeding the warning level doubled in the wet period but showed only a slight decrease in the subsequent dry period (Table 3).

## Water pollution under different hydrologic stages in the watercourses of the Biosphere Reserve

The sampling surveys performed in the Reserve included a severe drought (2008–2009) and an extended (December



◀ **Fig. 2** Major changes between the identified periods (historical, dam-regulated wet, and dam-regulated dry periods) of the hydrologic series of the Paraná River in the Paraná-Santa Fe cross section. **a** Flow duration curves. Additional *thin curves* show wetter (1903–1933) and drier (1934–1972) conditions of the historical period (*green*) and two conditions (1973–1982 and 1983–1999) of the wet period (*blue*). **b** Monthly flow medians. **c** Maximum and minimum flow per hydrologic year (1903–2014). *Horizontal lines*: median, 25 and 75 % percentiles in each period

2009 to June 2010) large flood (the only one recorded so far in the dry period) (Figs. 3 and 8c). More details are provided in Puig et al. (2015). Only those variables exceeding guideline levels and more likely associated with hydrologic stages (i.e., with rather similar spatial values in some sampling) were included in this analysis of potential risk factors.

A spread out of *Microcystis aeruginosa*, a cyanobacterium potentially toxic even for humans, was recorded during a high-flow pulse in La Niña year, in October, but mainly in December 2008 (Fig. 3), when water temperature exceeded 26 °C. In December, the density of this species (Fig. 8a) showed similar values in the main rivers (mean, 0.8; max, 1.9 colonies/mL), and lower values ( $\leq 0.2$  colonies/mL) in two streams (Fig. 1f). A density of *M. aeruginosa* similar to that of the main rivers of the Reserve was also recorded in the Paraná Pavón River, which crosses the middle Delta through an area rich in shallow lakes (Fig. 1e), 10 days before. Simultaneously, a bloom of this species (50 colonies/mL) was found in an adjacent lake (Gorosito Lagoon; depth, 3 m) temporarily connected with this river branch (Fig. 1e, g). Moreover, a *Dolichospermum* species, another potentially toxigenic cyanobacterium that was also abundant in this lake (13 colonies/mL), was detected in very low density ( $< 0.04$  colonies/mL) in the Paraná Pavón River and in some Reserve sites. The high-flow pulse in the Paraná Guazú River that was associated with these records of cyanobacteria showed a continuous rise since little before October, the maximum flow in the sampling date of the Paraná Pavón River and its adjacent lagoon (December), and began to fall on the sampling date of the Reserve watercourses (Fig. 8c). The distribution of *M. aeruginosa* in the Reserve suggests its transfer and dispersal by water from upstream, for example, from shallow lakes under bloom condition in the middle Delta, such as the above mentioned lagoon. The maximum of the high-flow pulse of La Niña year allowed the connectivity between this lagoon and a Paraná River branch. The connection between successive branches of the Paraná River (Pavón-Ibicuy-Guazú, Fig. 1e) provides a way for the arrival of inocula of this species in the lower Delta and their further dispersal by the final network of distributaries.

Several variables exceeded regulation levels during one or both samplings during the drought (February and April 2009) (Fig. 8b). In February, the concentration of *E. coli* was very similar in the six sites sampled (mean, 414 MPN/100 mL; Fig. 8b) and exceeded the national recommended value

(126 MPN/100 mL), as well as the USEPA international value (200 cfu/100 mL) for aquatic life protection and recreational use. The concentration of lead was over the detection level in five of the six sites sampled, where it exceeded the level of aquatic life protection (1 µg/L) established by the National Law of Hazardous Waste and even the national recommended value for recreational use (19.5 µg/L) in two sites (Fig. 8b). The cadmium concentration (0.5 µg/L) exceeded the level for aquatic life protection (0.2 µg/L) established by the National Law of Hazardous Wastes, whereas the concentrations of ammonium (mean, 0.17 mg/L) exceeded the level established for human drinking (0.05 mg/L) by the same regulation in all the sites sampled (Fig. 8b). The iron concentrations exceeded the national recommended value for aquatic life protection (1.37 mg/L) and the value for human drinking water (0.3 mg/L) established in several regulations (such as the Argentine Food Code, the National Law of Hazardous Wastes, and WHO) in all the samples. The iron concentrations were even high in February (mean, 7 mg/L) and doubled in April (mean, 14 mg/L). Manganese concentrations were similar to the guideline levels for both uses in February (0.1 mg/L) and exceeded them in April, when they also doubled (0.2 mg/L).

The ammonium concentrations (0.07–0.08 mg/L) exceeded the level for human drinking water (0.05 mg/L) established by the National Law of Hazardous Wastes with the overflow of levees (December 2009) by the flood of El Niño year.

## Discussion and conclusions

### Recent changes in the flow regime of the Lower Paraná River

When the hydrologic system under evaluation was subjected to an abrupt change, such as the construction of a dam, the flow regime analysis that is suggested is the calculation of the IHA and EFC parameters for two periods: pre- and post-impact. When the system was subjected to a long-time accumulation of human modifications, the analysis that is suggested is the evaluation of trends by linear regressions (TNC 2011). A more appropriate strategy to provide support for the decision about the application of the IHA software would be the previous analysis for change-point detection and the evaluation of trends in the significant segments identified (or in the complete series in case of no significant change points). Change-point and trend analyses are very useful for the detection of nonstationarity in time data series and may also be appropriate to support the decision on the strategy for the IHA and EFC application to the daily flow data series. In many hydrologic series analyses, only one of these two tests was applied or both were performed in the inverse sequence. In this study, trend

**Table 2** Indicators of Hydrologic Alteration and Environmental Flow Components in the historical (H: 1903–1972), dam-regulated wet (W: 1973–1999), and dam-regulated dry (D: 2000–2014) periods estimated from daily flows of the Lower Paraná River at the Paraná-Santa Fe section (upstream of the Delta)

IHA and EFC parameters	Medians <sup>a</sup>			Change in medians <sup>b, c</sup>				Change in variability			
	Hist.	Wet	Dry	%		<i>p</i>		Direction		<i>p</i>	
				H-W	H-D	H-W	H-D	H-W	H-D	H-W	H-D
September flow	10,430	16,850	13,240	<b>62</b>	<b>27</b>	$1 \times 10^{-9}$	$2 \times 10^{-4}$	<b>I</b>	<b>D</b>	$4 \times 10^{-2}$	$2 \times 10^{-2}$
October flow	10,900	17,790	15,130	<b>63</b>	<b>39</b>	$3 \times 10^{-7}$	$2 \times 10^{-3}$	<b>I</b>	<b>D</b>		$3 \times 10^{-2}$
November flow	13,160	18,350	16,540	<b>39</b>	<b>26</b>	$8 \times 10^{-6}$	$1 \times 10^{-2}$	<b>I</b>	<b>D</b>		
December flow	13,520	17,740	15,560	<b>31</b>	<b>15</b>	$1 \times 10^{-4}$		<b>D</b>	<b>D</b>		$4 \times 10^{-3}$
January flow	15,150	19,110	15,700	<b>26</b>	<b>4</b>	$3 \times 10^{-3}$		<b>I</b>	<b>D</b>		
February flow	17,970	22,370	16,330	<b>24</b>	<b>-9</b>	$3 \times 10^{-4}$		<b>I</b>	<b>D</b>		
March flow	20,120	23,810	16,990	<b>18</b>	<b>-16</b>	$4 \times 10^{-3}$		<b>I</b>	<b>D</b>		
April flow	19,850	20,880	18,620	<b>5</b>	<b>-6</b>			<b>D</b>	<b>D</b>		
May flow	16,010	20,410	17,990	<b>27</b>	<b>12</b>	$1 \times 10^{-3}$		<b>D</b>	<b>D</b>		
June flow	15,410	20,350	16,490	<b>32</b>	<b>7</b>	$2 \times 10^{-4}$		<b>I</b>	<b>D</b>		$3 \times 10^{-2}$
July flow	14,230	20,580	15,970	<b>45</b>	<b>12</b>	$9 \times 10^{-5}$		<b>I</b>	<b>D</b>		
August flow	11,400	17,940	15,260	<b>57</b>	<b>34</b>	$1 \times 10^{-7}$	$1 \times 10^{-3}$	<b>I</b>	<b>D</b>		
1-day minimum flow	7910	12,850	11,660	<b>62</b>	<b>47</b>	$2 \times 10^{-12}$	$9 \times 10^{-8}$	<b>I</b>	<b>D</b>		
3-day minimum flow	7925	12,870	11,730	<b>62</b>	<b>48</b>	$2 \times 10^{-12}$	$8 \times 10^{-8}$	<b>I</b>	<b>D</b>		
7-day minimum flow	7950	12,900	11,910	<b>62</b>	<b>50</b>	$1 \times 10^{-12}$	$8 \times 10^{-8}$	<b>I</b>	<b>D</b>		
30-day minimum flow	8436	13,450	12,580	<b>59</b>	<b>49</b>	$5 \times 10^{-12}$	$5 \times 10^{-7}$	<b>I</b>	<b>D</b>		
90-day minimum flow	10,400	16,040	13,530	<b>54</b>	<b>30</b>	$3 \times 10^{-10}$	$7 \times 10^{-5}$	<b>I</b>	<b>D</b>		$1 \times 10^{-3}$
1-day maximum flow	24,970	32,000	24,060	<b>28</b>	<b>-4</b>	$2 \times 10^{-4}$		<b>I</b>	<b>D</b>		
3-day maximum flow	24,790	31,580	24,060	<b>27</b>	<b>-3</b>	$2 \times 10^{-4}$		<b>I</b>	<b>D</b>		
7-day maximum flow	24,570	31,220	24,060	<b>27</b>	<b>-2</b>	$3 \times 10^{-4}$		<b>I</b>	<b>D</b>		
30-day maximum flow	23,430	30,540	22,660	<b>30</b>	<b>-3</b>	$2 \times 10^{-4}$		<b>I</b>	<b>D</b>		
90-day maximum flow	21,020	26,650	21,390	<b>27</b>	<b>2</b>	$4 \times 10^{-4}$		<b>D</b>	<b>D</b>		
Base flow index	0.55	0.65	0.70	<b>17</b>	<b>26</b>	$7 \times 10^{-6}$	$5 \times 10^{-7}$	<b>D</b>	<b>D</b>		
Date of minimum flow	271	282	296	<b>6</b>	<b>14</b>			<b>I</b>	<b>I</b>		
Date of maximum flow	96	93	93	<b>-1</b>	<b>-2</b>			<b>I</b>	<b>I</b>		
Low-pulse frequency	2.13	0.19	0.40	<b>-91</b>	<b>-81</b>						
Low-pulse duration	27	12	15	<b>-56</b>	<b>-44</b>						
High-pulse frequency	1.40	2.22	1.47	<b>59</b>	<b>5</b>						
High-pulse duration	58	74	47	<b>27</b>	<b>-19</b>			<b>I</b>	<b>D</b>	$4 \times 10^{-2}$	
Rise rate	164.8	179	158	<b>9</b>	<b>-4</b>	$3 \times 10^{-2}$		<b>D</b>	<b>D</b>		
Fall rate	-151	-168	-140	<b>11</b>	<b>-7</b>	$2 \times 10^{-2}$		<b>D</b>	<b>D</b>		$8 \times 10^{-3}$
Number of reversals	34	34	59	<b>0</b>	<b>74</b>		$4 \times 10^{-9}$	<b>I</b>	<b>I</b>		
Extreme-low flows	Peak (minimum)	8321									
	Duration	37									
	Date of peak	292									
	Frequency	1.41	0	0	<b>-100</b>	<b>-100</b>					
High flows	Peak (maximum)	19,750	19,690	18,620	<b>0</b>	<b>-6</b>	$2 \times 10^{-2}$	<b>D</b>	<b>D</b>		$7 \times 10^{-3}$
	Duration	16	20	11	<b>25</b>	<b>-31</b>		<b>D</b>	<b>D</b>		
	Date of peak	49	34	88	<b>-8</b>	<b>21</b>		<b>I</b>			
	Frequency	0.97	1.26	1.80	<b>30</b>	<b>85</b>					
	Rise rate	166	180	155	<b>8</b>	<b>-7</b>		<b>D</b>	<b>D</b>		
	Fall rate	-156	-151	-135	<b>-3</b>	<b>-14</b>		<b>D</b>	<b>D</b>	$4 \times 10^{-2}$	
Small floods	Peak (maximum)	27,170	28,860	27,860	<b>6</b>	<b>3</b>		<b>I</b>	<b>I</b>		

**Table 2** (continued)

IHA and EFC parameters	Medians <sup>a</sup>			Change in medians <sup>b, c</sup>				Change in variability			
	Hist.	Wet	Dry	%		<i>p</i>		Direction		<i>p</i>	
				H-W	H-D	H-W	H-D	H-W	H-D	H-W	H-D
Duration	113	129	133	14	17			D	D		
Date of peak	100	132	110	18	5				D		
Frequency	0.64	0.85	0.53	33	-17						
Rise rate	171	150	152	-12	-11			I	I		
Fall rate	-260	-128	-202	<b>-51</b>	-22	$2 \times 10^{-3}$		<b>D</b>	D	$7 \times 10^{-3}$	
Large floods <sup>d</sup> Peak (maximum)	46,800	48,570	40,550	4	-13						
Duration	222	303	269	37	21			<b>I</b>		$3 \times 10^{-2}$	
Date of peak	83	109	46	14	-20			I			
Frequency	0.06	0.22	0.07	289	17						
Rise rate	298	205	160	-31	-46						
Fall rate	-296	-237	-175	-20	-41			D			

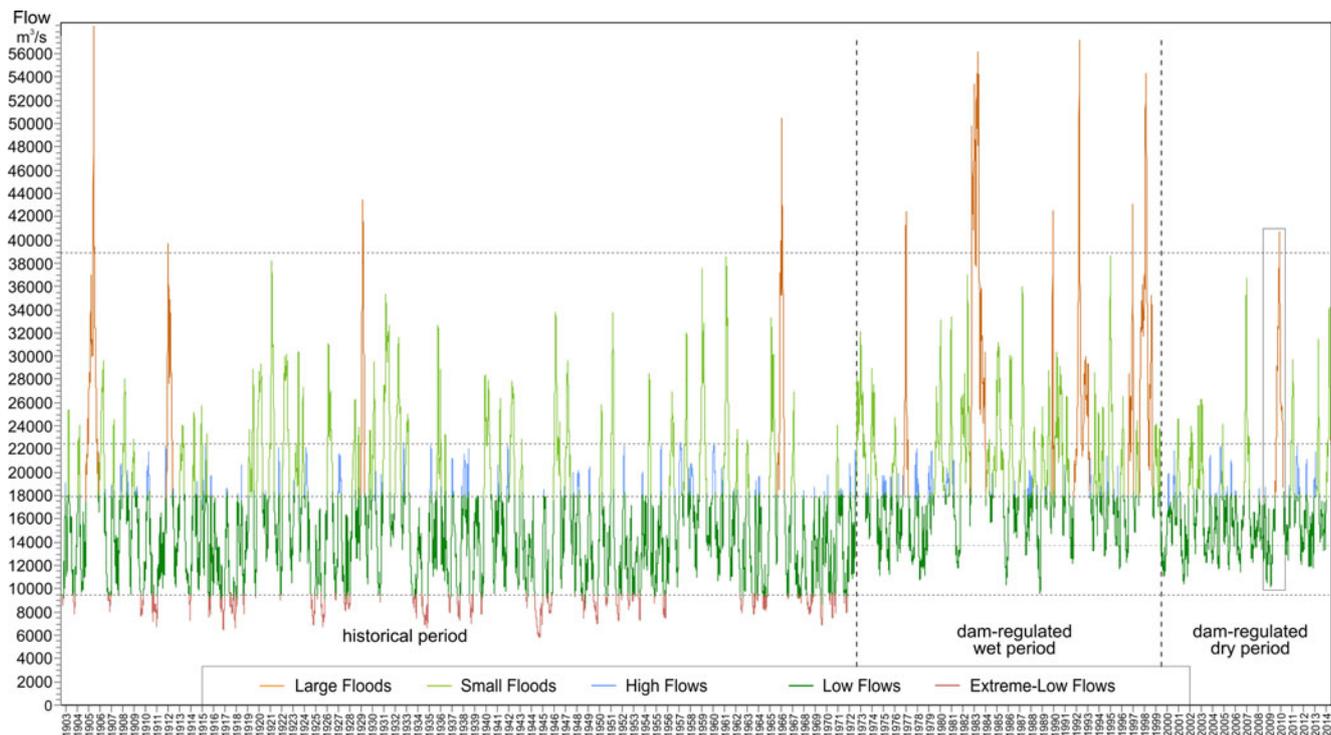
Medians in each period, percent change in values in each dam-regulated period with respect to the historical period value (numbers in bold for significant change), and the *p* value of significant comparisons (Wilcoxon’s test). Direction (I: increase; D: decrease) of the year-to-year change in variability in each dam-regulated period with respect to the historical period (in bold for significant changes), and the *p* value of significant comparisons (Siegel–Tukey’s test). Flows in m<sup>3</sup>/s, dates expressed as Julian dates (1–366), frequencies expressed by year (/y), duration in days (d), rates in m<sup>3</sup>/s/d

<sup>a</sup> Mean for frequencies, circular mean and circular variance for dates

<sup>b</sup> Specific percent change for dates (1 month  $\cong$  16 % of change, see text)

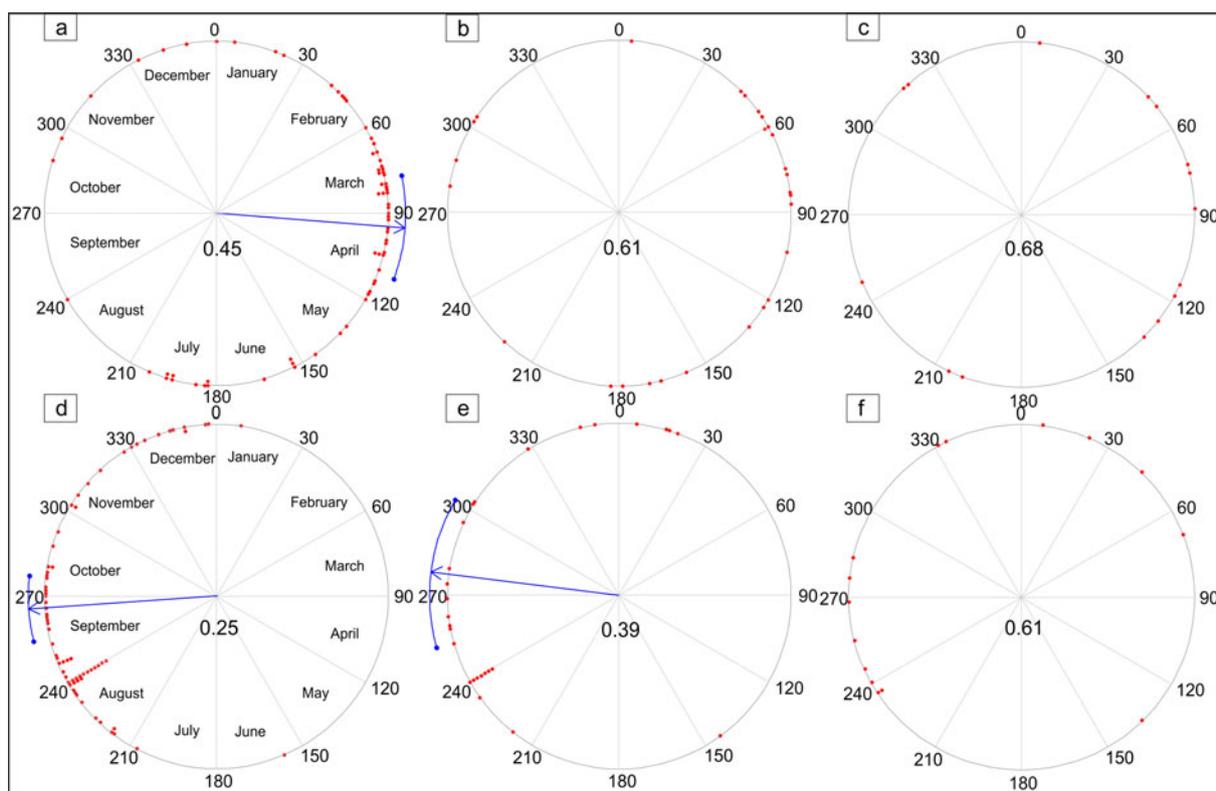
<sup>c</sup> Frequencies and dates not tested

<sup>d</sup> Only one large flood in the dry period



**Fig. 3** Environmental Flow Components of daily flows (1903–2014) of the Paraná River in the Paraná-Santa Fe cross section along the identified periods (historical, dam-regulated wet, and dam-regulated dry). Threshold criteria: large floods, 10 years of recurrence time; small floods, above the inundation flow; high-flow pulses, bankfull (~18,000 m<sup>3</sup>/s) to

inundation flows (~22,500 m<sup>3</sup>/s); extreme-low flows, below 10 % percentile of daily flows. A new threshold for dam-regulated periods (very-low flows) is included (*horizontal line*) and the period of samplings in the Delta Reserve rivers (two extreme hydrologic years) is distinguished (*rectangle*)

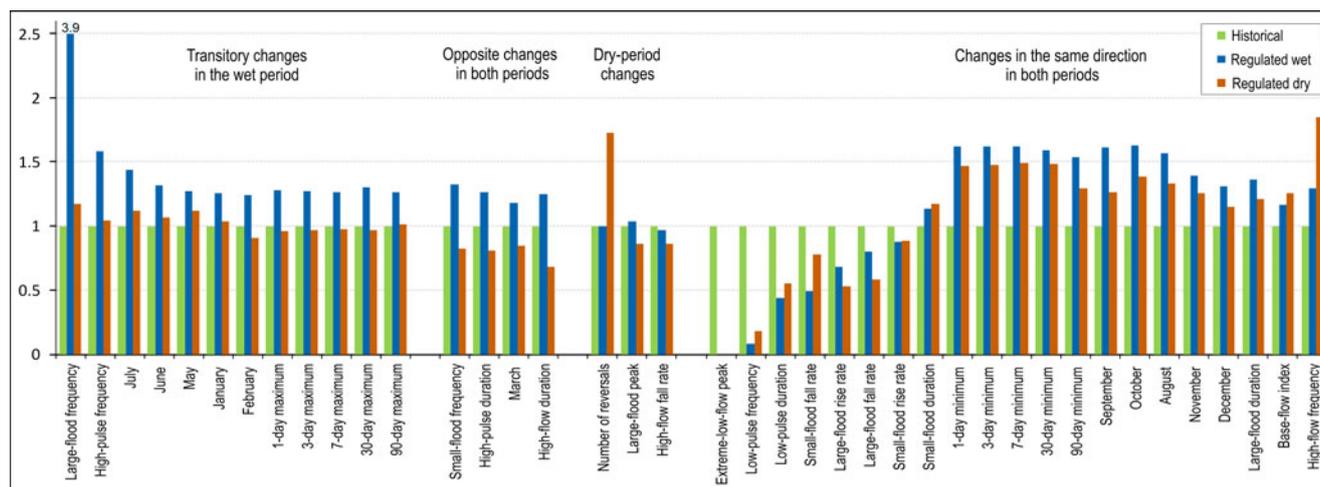


**Fig. 4** Distribution of the dates of maximum (a–c) and minimum (d–f) flow per hydrologic year in the historical (a, d), dam-regulated wet (b, e), and dam-regulated dry (c, f) periods. Each Julian date (converted to an angle) is plotted as a red point in a circle, circular mean (see values

reconverted to dates in Table 2) represented by an arrow, and its 95 % confidence interval plotted in blue (mean not plotted when data concentration is too low). Circular variance value (0–1 range) included in each circle

analysis follows change-point analysis because that is considered more appropriate and concordant with the fundamentals provided in Villarini et al. (2009).

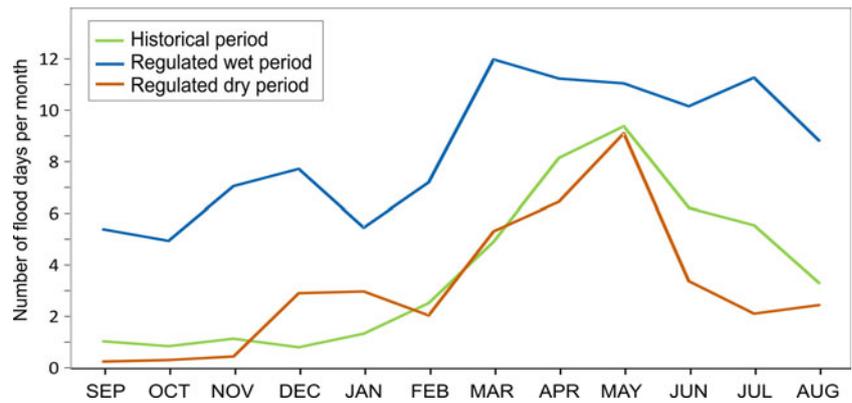
In this study, the degree, direction, and statistical significance of changes in the flow regime of the Lower Paraná River were assessed. The relatively complex flow pattern of this river makes



**Fig. 5** Proportion and direction of change in the dam-regulated wet and the dam-regulated dry periods with respect to each value in the historical period. The selected IHA and EFC parameters (change >15 % at least in

one dam-regulated period) were grouped by the kind of change observed. Fall rates expressed as positive values; dates excluded due to their specific scale of change

**Fig. 6** Monthly median number of flood days in the San Pedro station in each period (historical, dam-regulated wet, and dam-regulated dry periods)



the detection of changes more challenging. There is a general consensus that the flow regimes of river systems have been globally altered by the combined impacts of climate variability and human activities (Li et al. 2015), as is the case in this river. The flow duration curves evidenced notable changes in the two altered periods, in comparison with relatively minor variations within the historical period. The wet and the dry periods considered in this study are likely related to large-scale climatic variability. The warm phase of the Pacific Oscillation after the late 1970s is consistent with the more frequent and marked El Niño events mainly recorded in the wetter conditions (1983-1999) of the wet period in the Paraná River. Likewise, the cold phase initiated around 2000 that favors an increased frequency in La Niña events may induce drier conditions in regions where it generates droughts (Wang et al. 2014), as in the Paraná River.

Our analyses evidenced several changes in the flow regime of the Lower Paraná River after the early 1970s. The parameters that changed only in the wet period, such as the frequency of high pulses and large floods or the 1- to 90-day maximum, likely reflect the dominant humid feature of this period. Also, the parameters that increased in the wet period and decreased in the dry period, such as the small-flood frequency, high-pulse and high-flow duration, appear to be associated with the respective

dominant climatic feature of each contrasting period. However, numerous parameters showed changes in the same direction in both altered periods in comparison with the historical one. For example, the extreme-low flows disappeared, the frequency and duration of the low pulses and the rise and fall rates of small and large floods decreased, and the 1- to 90-day minimum and the flow of spring months increased. Climatic features are not likely the main drivers of these changes, as may be considered for the marked increase in reversals observed in the dry period.

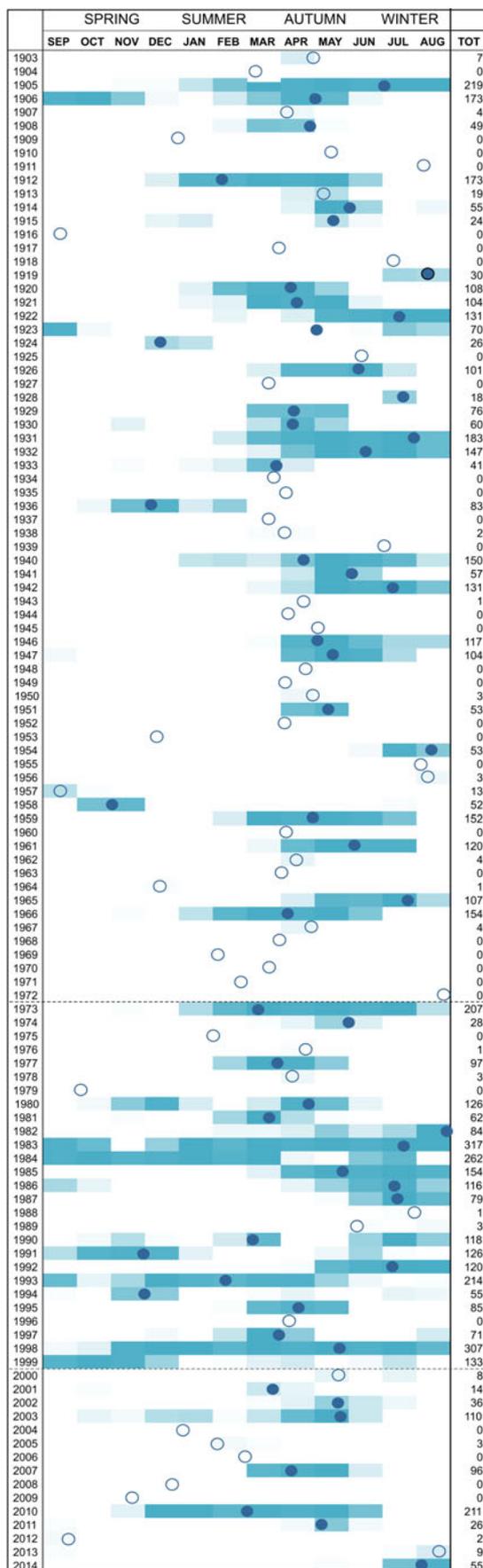
Besides climate variability, high land-use change and river regulation by dams contribute to flow regime changes. Localized deforestation usually causes a direct increase in surface runoff due to evapotranspiration reduction. However, large-scale deforestation can indirectly impact regional climate, leading to complex feedbacks and variable responses in river flow, depending on the balance between the induced reduction in evapotranspiration and in precipitation (Lima et al. 2014). Also, increasing human land-use change in the Amazon basin may potentially alter its additional atmospheric moisture contribution to the Paraná River basin.

The current high total upstream dammed volume (equivalent to about a half of the annual Lower Paraná River flow) reflects a moderate to high potential of flow regime alteration, according to

**Table 3** Flood characteristics in the San Pedro station (middle Delta) in the different periods (historical, dam-regulated wet, and dam-regulated dry)

	Historical period (1903–1972)	Wet period (1973–1999)	Dry period (2000–2014)
Median number of flood days	83	119	36
Median duration of maximum uninterrupted flood	61	86	40
Mean date of the flood onset (Julian date)	88	59	80
Variance of the onset date of flood (0–1 range)	0.42	0.81	0.62
Mean date of the maximum level (Julian date)	123	122	87
Variance of the maximum level date (0–1 range)	0.51	0.66	0.72
Mean frequency of years without flood	0.39	0.10	0.27
Days above the warning level (3 m)	988	1083	138
Days above the evacuation level (3.6 m)	270	540	53
Ratio: ≥ evacuation level versus ≥ warning level days	0.27	0.50	0.38

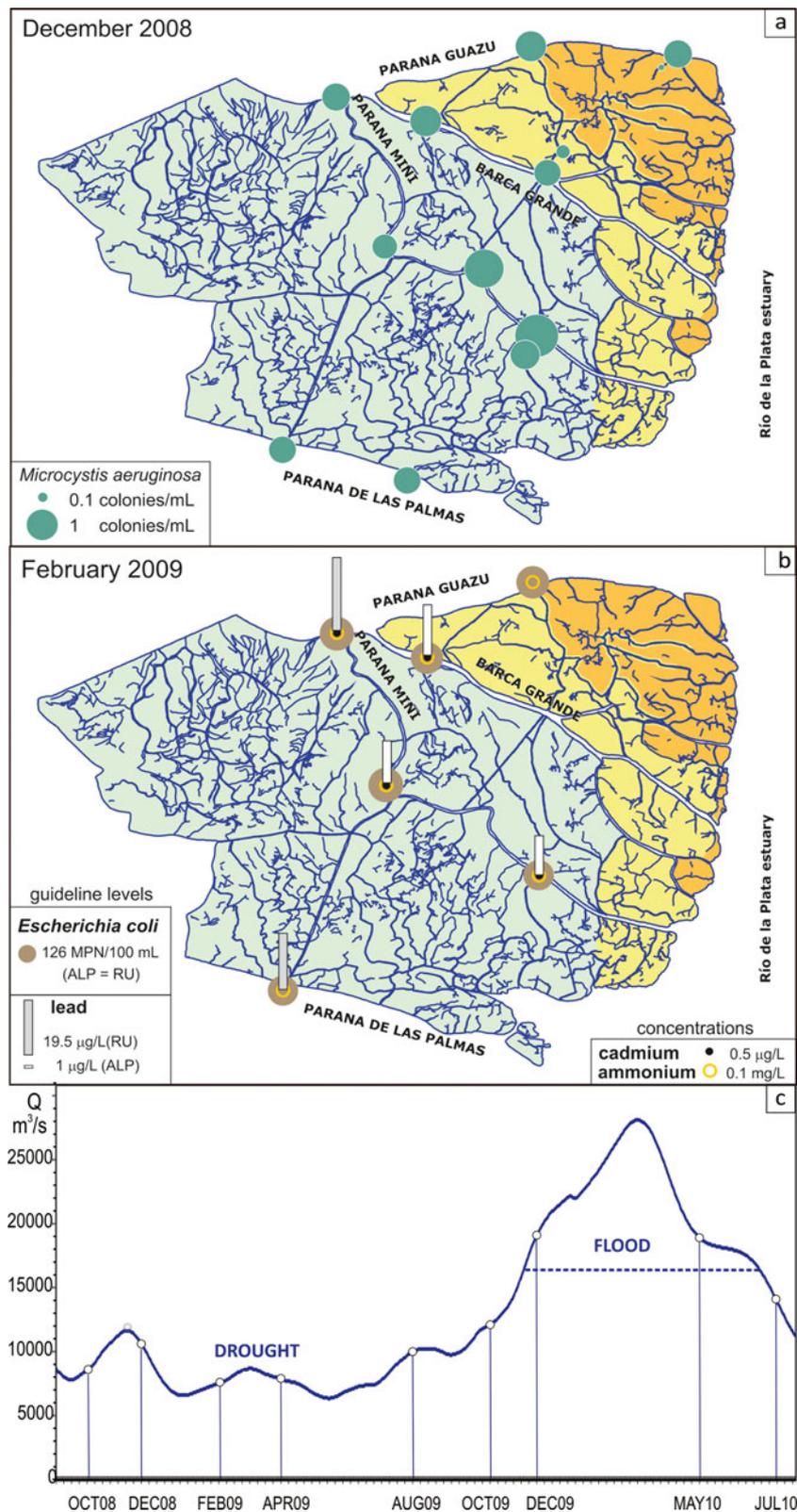
Upper panel: annual parameters estimated (considering at least seven flood days) from the number of days per hydrologic year or from Julian dates (by circular statistics, see text). Lower panel: total number of specific days and respective ratio for each complete period



◀ **Fig. 7** Floods (water level  $\geq 2.40$  m) in the San Pedro gauge station in each hydrologic year along the identified periods (historical, dam-regulated wet, and dam-regulated dry) of the data series. Monthly flood days denoted by blue color intensity; date of maximum hydrometric level indicated by a circle (dark blue circle: flood of at least seven uninterrupted days); total number of flood days per hydrologic year in the right column

FitzHugh (2014) criteria. Rocha (2010) applied the IHA to gauge station data of the last fluvial stretch of the Upper Paraná River, downstream of most Brazilian dams, for the comparison of two periods respectively considered by this author as pre-damming (1920–1971) and post-damming (1983–2001). These periods covered part of the historical and mainly the wetter segment of our study, respectively. In general, both studies found an increase in the monthly flow magnitude, with higher values of percent change (calculated from means of Rocha 2010) from July to November ( $\geq 40$  %). The highest change in the Upper Paraná was observed in August and September, whereas that in the Lower Paraná was observed in September and October, reflecting a time lag between these river sectors. In both studies, the minimum and maximum flow values increased, being the minima more affected; the low pulse decreased drastically in frequency and in the variability of its duration; and the high-pulse frequency as well as the rise and fall rates increased. Considering extensive studies (Magilligan and Nislow 2005; Poff et al. 2007; McManamay et al. 2012), the increase in the 1- to 90-day minimum flows and in the number of reversals (dry period), the decrease in high-pulse duration (dry) and in the rise and fall rates (small and large floods), and the change in the seasonal distribution of flows are in concordance with some general significant flow changes by dams that have been found across the USA. Some flow characteristics that evidenced a strong persistent change along both altered periods may reflect a homogenization trend resulting from the cumulative effect of dams. The lack of detection so far of the extreme-low-flow component has ecological relevance, because this component, for example, may affect the fluvial water chemistry and may allow native species to outcompete generalist invasive species that are not adapted to the extreme conditions associated with these events (TNC 2011). The “homogenization regime” has been associated with dams operating mainly for hydroelectricity generation throughout the year, for example, in Canada (Assani et al. 2006) and the USA (Magilligan and Nislow 2005). Precisely, the high proportion (almost 90 %) of energy generated by hydroelectric plants in Brazil (Valverde and Marengo 2014) suggests that the progressive attenuation observed of the seasonal distribution of monthly flows may be a consequence of the dominant operation regime of these upper basin dams.

In San Pedro, the increase in number of flood days per hydrologic year and the decrease in their monthly seasonality and in the proportion of years without inundation appear as particularities of the wet period. The opposite change (increase in wet period and decrease in dry period) in the number



**Fig. 8** Several potential risk factors detected in watercourses of the “Paraná Delta” Biosphere Reserve during the 2008–2010 samplings. **a** Density of colonies (~600–1200 cells) of the cyanobacterium *Microcystis aeruginosa* in the sampling sites of the Reserve in December 2008. **b** Concentrations of lead, cadmium, and ammonium and of the fecal bacterium *Escherichia coli* in the main rivers of the Reserve in

February 2009. *ALP* aquatic life protection and *RU* recreational use guideline levels. **c** Flows of the Paraná Guazú River (estimated by a hydrologic model) and their values at sampling dates in the Reserve (the sampling date in Paraná Pavón River and Gorosito Lagoon in the middle Delta is distinguished by a double circle)

of maximum uninterrupted flood days may reflect respective climate features of each altered period. In contrast, the increase in the proportion of days above the evacuation level as well as in the variability in dates of maximum hydrometric level and in dates of flood onset in both periods with respect to the historical period suggests other drivers. The increased proportion in evacuation levels poses a higher damage risk mainly for the Delta inhabitants. Changes such as the increased variability in the date of flood onset and in the date of flood maximum may affect biological cycles, for example, the reproduction of fishes (Oliveira et al. 2015). Fisheries in most of the Lower Paraná basin reflect a floodplain state disturbed by river regulation and other human activities, usually evidencing lower size and capture, higher fishing effort, and exotic species included in the captures (Quirós 2003). Since relatively few flood events have been so far recorded in the current dry period, additional data from floods in coming years will improve these analyses.

### Fluvial water pollution in the “Paraná Delta” Biosphere Reserve

The two extreme hydrologic years analyzed are representative of the range of conditions in the more regulated period, as considered by Marchetti et al. (2016). The last dry period favored the intensification and diversification of uses in the Delta (Baigún et al. 2008). In addition, various human activities outside the Delta region can affect the quality of its waters, as is the case of the urban-industrial corridor with active ports that extends along the right riverbank between Santa Fe and Buenos Aires cities, which brings mixed and usually not treated effluents. The variety of heavy metals, organic compounds, and pesticides in 15 deltaic affluents of the Paraná River (Puig and Olguín 2011) estimated from data of three samplings in different years (SAyDS 2008) is a clear evidence of the water quality problems. The detection under the severe drought of hazardous heavy metals, such as lead and cadmium, in concentrations exceeding levels for aquatic biota protection and even in some cases for recreational use indicates that fluvial waters of this international reserve are not safe from generalized pollution. The heavy metals adsorbed on colloids or residing in the crystalline structure of minerals would be predominantly transported on suspended fine-grained phase (Depetris 2007), explaining their increase during the drought, when higher turbidity by suspended sediments has been recorded.

The current intensive and permanent cattle ranching in the upper and middle Delta favors the increased dung amount in water environments. The consequent contribution to organic and microbiological (parasites and pathogens) water pollution not only affects ecosystems but may also represent a risk to human and animal health. The detection of *E. coli*, a fecal coliform bacterium normally found in the intestine of humans

and other homeotherms, is an indication of harmful enteric pathogens, such as *Salmonella*, *Shigella*, enterovirus, *Cryptosporidium*, and *Giardia* (USEPA 2004). The deliberate burning of grasslands, a practice associated with intensive livestock, may increase the contribution of sediments and nutrients to aquatic environments. In 2008, an extended Delta area was burned and the fire particularly affected areas surrounding the environments sampled with cyanobacteria of the middle Delta. The recent development of rice crop in fluvial provinces (Santa Fe, Entre Ríos, and Corrientes) has generated not only the use of agrochemicals but also numerous small reservoirs for irrigation, increasing the water retention time. The further drainage of their waters to the fluvial system contributes with solutes, suspended particles, and microorganisms and may also affect the water quality.

The colonies of *M. aeruginosa*, dispersed by the Reserve rivers and favored by water temperature values close to the specific optimal (Paerl and Huisman 2009), may proliferate especially in Delta sites with even more favorable conditions (low water flow, higher nutrient concentration, wind protection, etc.) and are potential sources of the blooms of this species recorded in the Río de la Plata estuary (Andrinolo et al. 2007). This species may produce microcystin, which even in low concentrations under prolonged exposure can cause chronic effects, such as the formation of liver tumors (Chorus and Bartram 1999). Therefore, the detection of cyanobacteria in the Reserve means a warning of potential risk for its population, which daily drinks (after local treatment) and has contact with fluvial water. The marked increase in the frequency and duration of blooms of cyanobacteria is strongly associated with the increase in cultural eutrophication (Hallegraeff 1993), and the forecasted increase in global temperature due to climate change will favor their proliferations (Paerl and Huisman 2009).

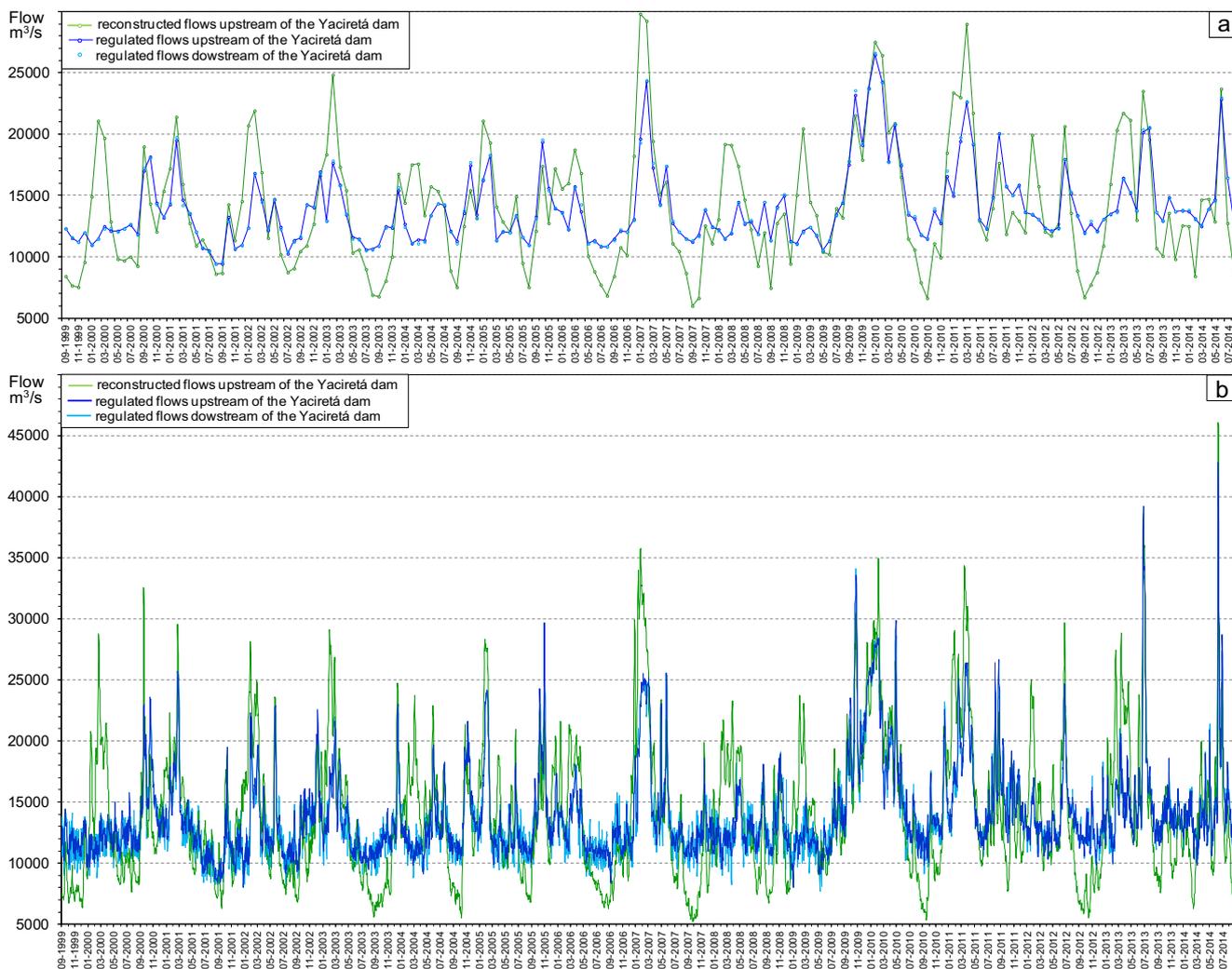
Higher ammonium values in the overbanking flood stage are in concordance with the increased export of nutrients with floods also recorded in the Middle Paraná River (Depetris 2007).

In summary, the emergence or the increase in risk factors from natural and mainly anthropogenic sources was associated with different hydrologic conditions. During the drought, the increased concentration of pollutants may be a consequence of the reduced Paraná River flow together with particulate loads from the Bermejo River. Ammonium values under overbanking flood condition may be associated with the nutrient additional contribution from island hypoxic environments with high organic matter (Puig et al. 2015). The high-flow pulse of the La Niña year would have favored the arrival of potentially toxigenic cyanobacteria from small lakes of the upper or middle Delta and their fluvial dispersal.

**Current and forecasted conditions**

The consideration of a control, such as fluvial stations upstream of all dams in this basin or a natural parallel basin with similar climatic conditions, seems an unviable approach to distinguish the effects of human direct influence from those of the climatic variability in a basin of subcontinental scale with a very high number of dams dispersed also in many tributaries. However, the comparison between altered flows and reconstructed flows estimated removing effects of dam regulation, reservoir evaporation, consumptive uses, and water diversions may provide a general view at least of these influences. Figure 9 shows mainly the cumulated regulation effect of upstream dams on the Paraná River flow in the zone of the last large dam (Yaciretá) during the current dry period. At monthly

scale (Fig. 9a), the reconstructed low pulses are almost eliminated, providing evidence of the cumulated regulation effect on the observed lack of record of extreme-low flows. In addition, the magnitude of the high pulses is frequently reduced or even eliminated in occasions (for example, in January–March 2000 or in February 2009), reflecting the effect of dam operation and eventual filling periods of large reservoirs. These alterations provide support for the reduction in monthly seasonality. In contrast, the effect of numerous run-of-the river dams operating for daily regulation (Fig. 9b), including the evident effect of the last large dam, increases the flow variability at daily scale. These daily effects are consistent with the increase in the number of reversals in the dry period. The regulation at both temporal scales may explain the increased variability in the dates of maximum and minimum flows.



**Fig. 9** Cumulated dam-regulation effect on the Paraná River flow in the zone of the Yaciretá reservoir (Fig. 1b) during the current dam-regulated dry period (a) at monthly scale (b) at daily scale. Reconstructed flows were estimated by the sum of the reconstructed flows downstream the

Paraná Upper basin in Brazil, i.e., downstream the Itaipú and Salto Caxias dams (see the “Sources of hydrologic data” section), and the calculated water contribution to the Paraná River section from Itaipú dam to Yaciretá dam

The hydrologic effects of these upstream dams, such as the lack of record of extreme-low flows and the strong seasonality attenuation, are detectable in the final sector of this huge basin, despite the large distance downstream the southernmost dam (>1000 km). This observation is discordant with the generalization that dam-related effects on the flow regime become less pronounced with distance downstream by the contribution of less or not regulated tributaries (Poff et al. 2007). Therefore, the optimization of the operation rules of the present dams should integrate energy supply for essential human needs with ecosystem integrity along this transboundary basin, avoiding the loss of valuable natural goods and services, as claimed in other studies (e.g., Oliveira et al. 2015). Considering the high number of new projected dams in South America, as well as in Asia, despite the limited evaluation of their effects, Kareiva (2012) points out that although alternative sources of energy may be considered, the productivity of a fishery may be irreplaceable. Likewise, considering the unprecedented boom in construction of hydropower dams in the world's most biodiverse river basins (Amazon, Congo and Mekong), Winemiller et al. (2016) point out that these projects often underestimate negative effects on biodiversity and critically important fisheries. Therefore, these authors claim that basin-scale analyses accounting for cumulative impacts from multiple dams and climate change are required.

The strong attenuation of the monthly flow seasonality and the increased variability in the dates of maximum and minimum river flow and in the dates of both flood onset and maximum level in the middle Delta have major ecological relevance, due to their potential to alter the seasonal synchrony of biological cycles (Poff et al. 2007). The change in San Pedro in the proportion of days over the evacuation level with respect to those over the warning level reflects that abrupt events may arrive in the Delta as little attenuated flood waves with intense effect, especially for the population, also in the current markedly dry period.

The evaluations in the Delta Reserve rivers encompassed opposite flow events that were extreme in magnitude and duration. The detection of more risk factors during the drought is in agreement with a review concluding that most quality problems in rivers are associated with reduced flows (Nilsson and Malm-Renöfält 2008). The lack of record of extreme-low flows may avoid a more intense concentration of the occasional pollution factors, but the loss of this component may induce other ecological problems, such as the proliferation of invasive alien species. Their proliferation in this basin, also favored by other factors, such as the intense passage of large cargo boats along the waterway in the main Paraná branch allowing fluvial navigation from the Atlantic Ocean (Hidrovia Project), may impact ecosystems and human activities (e.g., Boltovskoy and Correa 2015).

Among the most widely predicted consequences of climate change at a global scale are the increase in both the frequency and severity of a variety of extreme weather events, such as heavy rainfalls, floods, droughts, heat waves, and wildfires, each of

which can potentially impact water quality (Khan et al. 2015). In the Paraná basin, dry periods are projected to increase in duration and frequency (Valverde and Marengo 2014). Therefore, the fluvial water may transport concentrated pollutants more frequently. Various human activities and practices may favor the accumulation of compounds or organisms of potential risk in floodplain environments of the middle and upper Delta. The case of cyanobacterium dispersal highlights that the current increase in the number of flow reversals and in the frequency of high-flow pulses may more frequently provide connectivity with those environments, causing additional arrival of compounds and organisms in the lower Delta.

Although risk factors in the Reserve watercourses were only occasionally detected and mainly under a severe drought joint with a heat wave and wildfires (Puig et al. 2015), the more marked climatic variability since the early 1970s coupled with increasing human pressures poses a perspective of increased water quality risks for the biota of the Lower Paraná River and the inhabitants of the Delta Reserve. The results provide warning signals about possible difficulties in compliance with the human right of access to potable and healthy water, as well as the right to a healthy environment, which have been recognized by the United Nations (Capaldo et al. 2013). The occasional detections mentioned, despite the large flow of the river branches evaluated, emphasize the obsolescence of the paradigm of solving pollution by dilution. The lessons learned from the strong experience accumulated on a tributary of the Rhine River that has been affected by heavy mixed pollution (Ruhr River basin, Germany) indicate that pollution must be controlled as close to the respective source as possible, avoiding its dispersion (Imhoff et al. 1992). In the case studied, pollution dispersion must be avoided to protect not only the terminal Delta of this large basin but also neighboring systems, such as the binational estuary, which also provide valuable ecosystem services. While dealing with the transcendent goal of pollution control in the basin, future ecohydrologic studies may refine the specific hydrologic conditions under which different risk factors are frequently recorded, thus contributing to the local development of early warnings. An ecosystem approach linking research, population, and management sectors is advisable at least for the consideration of preventive and palliative temporary measures appropriate for the protection of the potentially affected population.

Finally, both the change-point detection followed by trend evaluation, as support for the selection of the strategy for the IHA software application, and the use of circular statistics for dates are recommended. Flow duration curves, IHA, and EFC are useful tools to monitor changes or trends of ecological and social relevance in intra-annual components of the flow regime and its year-to-year variability. Moreover, the application of tools like these to results of simulations of alternative anthropic interventions and scenarios should provide support to improve future decisions considering multiple objectives (Ziv et al. 2012; Arias et al. 2014).

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