Science of the Total Environment 571 (2016) 1392–1406

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Hydroclimatic and water quality trends across three Mediterranean river basins

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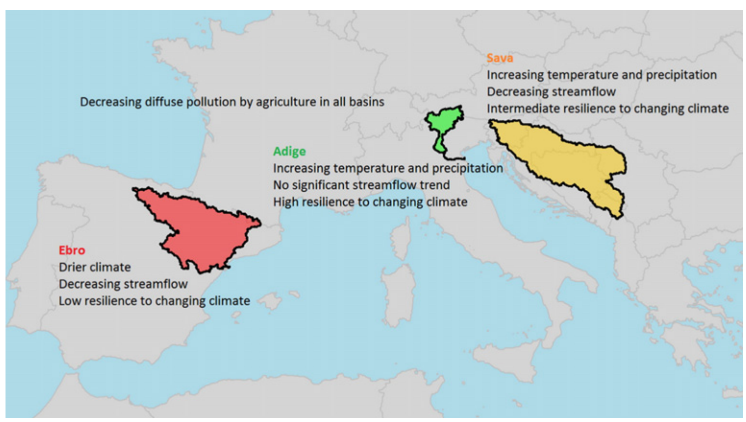
HIGHLIGHTS

- Trend analysis in three large Mediterranean river basins
- Contrasting hydroclimatic trends between alpine and continental river basins
- Decrease in nitrate pollution in all river basins
- Highest risk of water scarcity in Iberian Peninsula

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 June 2016
Received in revised form 14 July 2016
Accepted 14 July 2016
Available online 19 July 2016

Editor: D. Barcelo

Keywords:
Mediterranean river basins
Streamflow
Hydroclimatic trends
Water scarcity
Mann-Kendall trend analysis
Nitrate pollution trends

ABSTRACT

Water resources are under pressure from multiple anthropogenic stressors such as changing climate, agriculture and water abstraction. This holds, in particular, for the Mediterranean region, where substantial changes in climate are expected throughout the 21st century. Nonetheless, little attention has been paid to linkages between long-term trends in climate, streamflow and water quality in Mediterranean river basins. In the present study, we perform a comparative analysis of recent trends in hydroclimatic parameters and nitrate pollution in three climatologically different Mediterranean watersheds (i.e., the Adige, Ebro and Sava River Basins). Mann-Kendall trend analyses of annual mean temperature, precipitation and streamflow (period 1971 to 2010) and monthly nitrate concentrations, mass fluxes and flow-adjusted concentrations (period 1996 to 2012) were performed in these river basins. Temperature is shown to have increased the most in the Ebro followed by the Sava, whereas minor increases are observed in the Adige. Precipitation presents, overall, a negative trend in the Ebro and a positive trend in both the Adige and Sava. These climatic trends thus suggest the highest risk of increasing water scarcity for the Ebro and the lowest risk for the Adige. This is confirmed by trend analyses of streamflow time series, which indicate a severe decline in streamflow for the Ebro and a substantial decline in the Sava, as opposed to the Adige showing no prevailing trend. Concerning surface water quality, nitrate pollution appears to have decreased in all study basins. Overall, these findings emphasize progressive reduction of water resources availability in river basins characterized by continental climate (i.e., Ebro and Sava). This study thus underlines the need for adapted river management in the Mediterranean region, particularly considering strong feedbacks between

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http://dx.doi.org/10.1016/j.scitotenv.2016.07.102

hydroclimatic trends, freshwater ecosystem services and water resources availability for agriculture, water supply and hydropower generation.

1. Introduction

Water resources are under pressure from a variety of anthropogenic stressors such as industry, agriculture and tourism, which can lead to streamflow alteration and pollution. Changing climate is an additional stressor that can enhance the effects of these anthropogenic influences. For example, higher temperatures lead to increased evapotranspiration and thus, if not counterbalanced by increased precipitation, to declining streamflow (Lespinas et al., 2010; Pandžić et al., 2009). During the last decades, mean and extreme temperatures have been observed to increase in Mediterranean regions (Acero et al., 2014; El Kenawy et al., 2011; Giorgi and Lionello, 2008; Xoplaki et al., 2003), accompanied by seasonal reductions in precipitation (Del Río et al., 2011; Sousa et al., 2011; Vicente-Serrano and Cuadrat-Prats, 2007). Similarly, climate projections for the end of the 21th century indicate higher temperatures especially during summer, significant reductions of annual and summer precipitation, and decreasing soil water content in summer for the Mediterranean region (European Environment Agency, 2012; Giorgi and Lionello, 2008). At the same time, intensification of agriculture and hydropower production in the Mediterranean region have required increasing amounts of water and altered the hydrological regime of human-modified basins (Bellin et al., 2016; Graveline et al., 2014; Levi et al., 2015; López-Moreno et al., 2011; Majone et al., 2016, 2012; Zolezzi et al., 2009). Intensification of agriculture can also result in increased pesticide and fertilizer use and, consequently, deteriorate surface water quality (Bottarin and Tappeiner, 2010; Breeuwsma and Silva, 1992; Heathwaite, 2010; Lassaletta et al., 2009; Wyness et al., 2003; Zalidis et al., 2002). Hence, the Mediterranean region is particularly exposed to both changing climate and additional anthropogenic pressures. The combined effect of these pressures is likely to result in increased water scarcity, declining crop yields, less biodiversity and, ultimately, higher risks to human health (European Environment Agency, 2012).

In view of the various anthropogenic stressors on Mediterranean freshwater resources, it is crucial to identify ongoing trends, their drivers and their impact in order to determine suitable adaptive strategies for the management of water resources and regional land use policies. Whereas numerous studies have analysed climate trends in the Mediterranean region (see, e.g., the comprehensive reviews by García-Ruiz et al., 2011; and Merheb et al., 2016), there are fewer studies that jointly consider trends in climate and streamflow. Such analyses have been mostly performed either for catchments with a drainage area of <10,000 km^2 (e.g., García-Ruiz et al., 2010; Lespinas et al., 2010; Ludwig et al., 2004; Morán-Tejeda et al., 2010; Rivas and Koleva-Lizama, 2005) or in multi-basin approaches at the regional scale selecting one gauging station from each watershed (e.g., Kalayci and Kahya, 2006; Renard et al., 2008; Trigo et al., 2004), but much less frequently in a detailed manner for specific large Mediterranean watersheds (see, e.g., Levi et al., 2015; and Zanchettin et al., 2008). Moreover, little research has been conducted on feedbacks between streamflow and water quality trends in large Mediterranean watersheds. For example, several studies have focussed on trends in water quality parameters in the Iberian Ebro River Basin without explicitly considering the influence of long-term streamflow trends (Aguilera et al., 2015; Bouza-Deaño et al., 2008; Lassaletta et al., 2009). Similarly, previous research in the Adige has examined specific stressors locally, but a comprehensive assessment of multiple stressors at the river basin scale is still lacking (see e.g., Chiogna et al., 2016, for a case study review). In addition, data scarcity in large Mediterranean river basins can restrict analyses of streamflow or water quality trends to a relatively short time period or to a few gauging stations along the main river course (e.g., Bjelajac et al., 2013; Levi et al., 2015; Vrzel and Ogrinc, 2015). Hence, there are a limited number of studies on hydroclimatic trends in large Mediterranean river basins, and virtually no research on the linkages between long-term trends in climate, streamflow and water quality parameters in these river basins. Moreover, comparative studies discussing differences in these trends across Mediterranean regions are still lacking. Studies that do compare trend patterns in different Mediterranean regions are, in fact, mostly limited to temperature and precipitation analyses (e.g., Kelley et al., 2012; Norrant and Douguédroit, 2005; Philandras et al., 2011; Xoplaki et al., 2003). This study, on the contrary, aims at providing an integrated analysis of recent trends in climate, streamflow and nitrate concentrations (assumed as a proxy for diffuse pollution from agriculture), applied to three large Mediterranean river basins with different climatic and hydrologic conditions.

The river basins investigated in this study encompass different climatic conditions (i.e., alpine, continental and semi-arid) and have been selected for a detailed analysis of the effects of multiple stressors on aquatic ecosystems within the framework of the research project GLOBAQUA (Navarro-Ortega et al., 2015). They present substantial differences in projections of future climate as retrieved from General Circulation Models (European Environment Agency, 2012). As a consequence, this work can thus be considered as starting point for future investigations of hydro–meteorological and nitrate trends in Mediterranean catchments presenting similar climatology and water uses. Therefore, the objectives of the present work are (i) to analyse hydroclimatic and nitrate trends and associated stressors in each river basin, (ii) to identify links and feedbacks between hydroclimatic and nitrate trends in each basin, and (iii) to compare these basins with respect to their vulnerability and resilience to the identified drivers of change. The comparison between the study basins might be particularly beneficial, as the effect of changing climate might not be uniformly distributed among the three river basins despite similar climatic conditions, but rather depend on catchment-specific conditions (Botter et al., 2013).

2. Study basins

2.1. The Adige River Basin

The Adige River Basin is an alpine watershed located in the northeastern part of Italy (with a small part in Switzerland; Fig. 1). With a size of about 12,100 km^2, it is the third largest Italian river basin (after the Po and Tiber River Basins). The Adige River has a length of 409 km and drains into the Adriatic Sea. Mean streamflow registered at the most downstream gauging station of Boara Pisani is about 202 m^3 s^{-1} (Chiogna et al., 2016). Since the majority of the Adige drainage area lies in the Alpine region (Gumiero et al., 2009), we refer in the present work to the hydrological information available in the portion of the river basin located within the Autonomous Provinces of Trento and Bolzano. Elevation in the Adige reaches up to 3400 m a.s.l. and the long-term annual mean temperature (1961–1990) is 3 °C. Climate is typically alpine and characterized by dry winters, snow and glacier-melt in spring, and humid summers and autumns. Annual average precipitation is 1456 mm, but ranges between 400 and 500 mm in the upper Adige river valley and 1600 mm in the upper Avisio basin (period from 1961 to 1990; Gumiero et al., 2009). Land use in the Adige consists of forest (42%), agriculture (14.5%), grassland and sparse vegetation (both around 17%; Gumiero et al., 2009). Starting from the beginning of last century, with acceleration in the 50s, 30 large reservoirs have been built mainly for hydropower generation. Their total operational storage

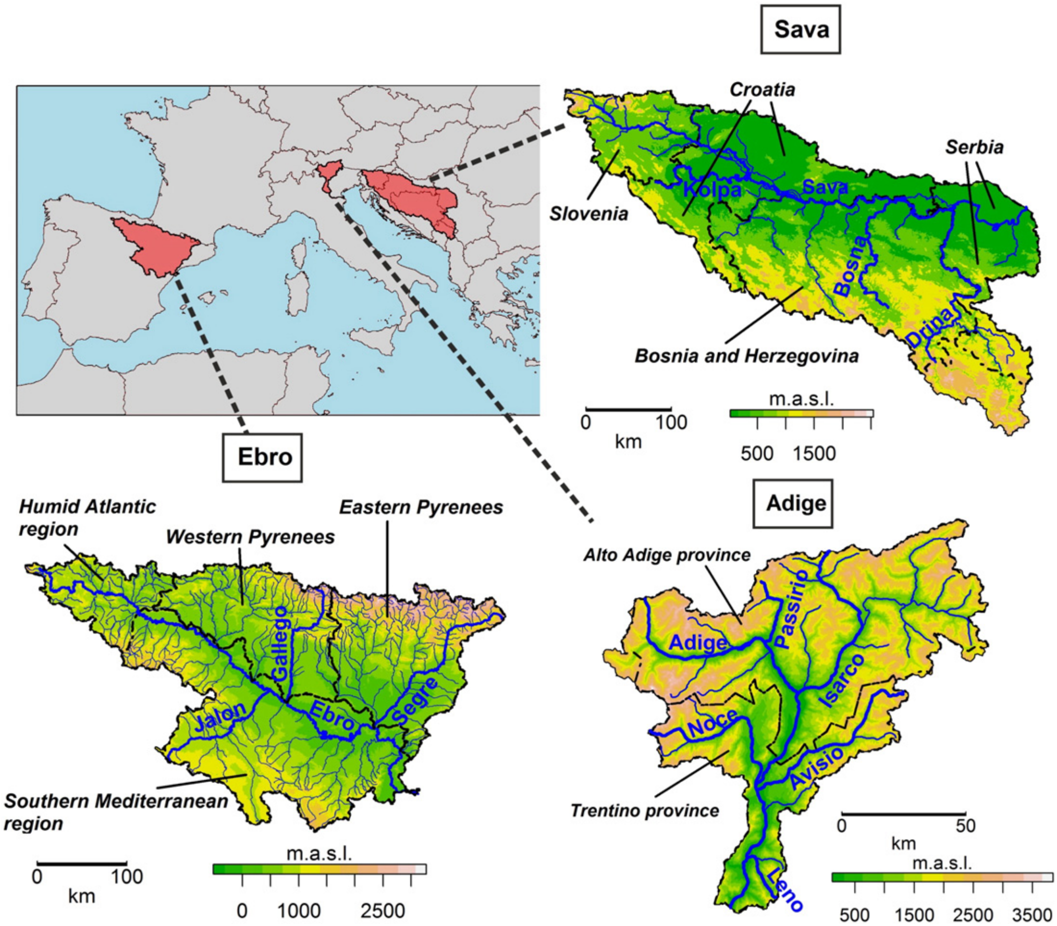

Fig. 1. Map presenting the locations of the study river basins: Ebro, Sava, and Adige with main regions and tributaries. Digital elevation models (DEMs) are also presented as coloured maps.

is about $560 \cdot 10^6$ m^3, which corresponds to 8.5% of the long-term mean annual streamflow volume. Hydropower exploitation has induced significant streamflow alterations in the basin and its main tributaries (Majone et al., 2016), particularly at intermediate and low flow regimes (Zolezzi et al., 2009).

2.2. The Ebro River Basin

The Ebro River Basin is located in northern Spain with small parts in France and Andorra (Fig. 1). It extends from the Pyrenees and the Cantabrian Range in the north (maximum altitude of >3000 m a.s.l.) to the Iberian Range in the south (up to >2000 m a.s.l.) and the Coastal Range (up to 1200 m a.s.l.) in the east (López-Moreno et al., 2011). The Ebro River has a length of 910 km and drains into the Mediterranean Sea with a mean streamflow of 425 m^3 s^{-1}. With a catchment area of 85,362 km^2, the Ebro is the largest river basin of Spain (Sabater et al., 2009). Annual mean temperature between 1920 and 2000 was 11.4 °C (with temperature extremes of below −20 °C in winter and up to 40 °C in summer), and mean annual precipitation in the same period was 620 mm (with extremes of 3000 mm yr^{-1} in the Pyrenees and <100 mm yr^{-1} in the Ebro river valley; Sabater et al., 2009). The climate is mostly of continental Mediterranean type and ranges from semi-arid in the centre of the river valley to oceanic in the Pyrenees and Iberian Mountains (Sabater et al., 2009). The main land use types are agriculture (47.1%), natural grassland (25.5%), and forest (22.3%; Sabater et al., 2009). The main river course and tributaries of the Ebro are regulated by 187 reservoirs having a total storage capacity of about $7500 \cdot 10^6$ m^3 (according to the Confederación Hidrográfica del Ebro; CHE), which corresponds to 57% of the average annual streamflow volume (Batalla et al., 2004). The main function of the reservoirs is to provide water for hydropower use and irrigation of agricultural land.

2.3. The Sava River Basin

The Sava River is a transboundary river and flows through 6 countries (i.e., Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, and a minor part in Albania; Fig. 1). It is composed of two headwaters (i.e., the Sava Dolinka and the Sava Bohinjka) and has a length of 945 km excluding the headwaters (ISRBC, 2013). The Sava River drains into the Danube in Belgrade (Serbia) with an average streamflow of about 1700 m^3 s^{-1} (Komatina and Grošelj, 2015). Having a catchment area of 97,713 km^2, the Sava is the second largest tributary basin of the Danube after the Tisza River Basin. Altitudes in the Sava range from 71 m a.s.l. at the catchment outlet to >2860 m a.s.l. in the Slovenian alpine headwaters (ISRBC, 2013). Annual mean temperatures between 1971 and 2000 ranged from 6 °C in the mountain regions to 13 °C close to the river mouth (Ogrinc et al., 2015). Mean annual precipitation between 1961 and 1990 ranged from 800 to 1600 mm and reached >3000 mm in the Alpine region in Slovenia (Ogrinc et al., 2008). Climatic conditions along the Sava River range from alpine to pannonian and continental. The main land cover types are agriculture (42%), and forest and semi-natural areas (55%; based on Corine Land Cover 2006, European Environment Agency, 2013). Forest is the main land cover in the upstream part in Slovenia and south of the main river course. Since the beginning of last century, 19 large storage reservoirs have been constructed along the Sava River with the main purpose of hydropower generation (Levi et al., 2015).

3. Data and methods

To ensure comparability between the three river basins, the study periods were set to the longest time frame possible providing sufficient data in all basins. This yielded two different study periods for the analysis of streamflow and water quality, respectively. In general, climate and streamflow were analysed for the period 1971 to 2010, with the exception of the Ebro where climate data were available only until 2007. For the latter, the period from 2008 to 2010 was disregarded in the analysis. Trends in monthly streamflow, nitrate concentration and nitrate mass flux were calculated in all basins for the period 1996 to 2012. Restriction to this time frame was necessary due to the limited availability of nitrate measurements in the Sava.

3.1. Meteorological data

The rationale in the selection of meteorological data was to use the highest spatial resolution available in each river basin (i.e., 1 km for the Adige, around 10 km in longitude and 14 km in latitude for the Ebro, and around 20 km in longitude and 27.5 km in latitude for the Sava). For the Adige, this was based on data from about 200 hydro-meteorological stations since 1930, including daily precipitation and temperature data provided by the meteorological offices of the Province of Trento (http://www.meteotrentino.it) and Bolzano (http://www.provincia.bz.it/meteo/home.as). The spatial distribution of temperature and precipitation variables was obtained by means of Kriging with External Drift (KED) over a squared grid of 1 km resolution. Cross validation was applied to choose the best interpolation scheme and variogram model parameters.

For the Ebro, temperature and precipitation data were taken from version v4 of the Spain02 dataset (Herrera et al., 2012; freely available at http://meteo.unican.es/thredds/catalog/Spain_CORDEXgrids/catalog.html). This dataset provides gridded data of average daily precipitation and temperature at 0.11°-resolution in rotated coordinates (according to Euro-CORDEX) for Spain and the Balearic Islands between 1971 and 2007. The data were derived from a quality-controlled subset of point measurements of the Spanish Meteorological Agency (AEMET). We opted for this dataset because of its finer spatial resolution compared to the E-OBS gridded dataset available for entire Europe (Haylock et al., 2008). For this study, the temperature and precipitation grids were first mapped on a 0.125° regular grid and then cropped to the Ebro area.

For the Sava, temperature and precipitation data were extracted from version 12.0 of the E-OBS gridded dataset (Haylock et al., 2008; freely available at http://www.ecad.eu/download/ensembles/download.php#datafiles). This quality-controlled dataset comprises daily gridded data of average temperature and precipitation from 1950 to June 2015 at different resolutions for entire Europe. In this analysis, the grids with the finest resolution (0.25° regular grid) were used and cropped to the area of the Sava.

3.2. Streamflow data

In the Adige, streamflow data have been continuously registered at 58 gauging stations (data provided by the hydrological offices of the Province of Trento, http://www.floods.it/public/index.php; and Bolzano, http://www.provincia.bz.it/hydro/index_i.asp). Some of them provide daily historical data for the last two decades, while others have been continuously operated since 1920 (e.g., the gauging station in Trento). High-resolution data are also available with a time step of 10 min. For this study, sub-daily time series were aggregated to daily scale in order to extend and fill the gaps of the daily time series.

In the Ebro, mean daily streamflow was obtained from the Confederación Hidrográfica del Ebro (CHE). A total of 296 streamflow gauges with data until September 2012 are listed in the CHE database, but the amount of years with streamflow measurements greatly varies between stations. We pre-selected stations with streamflow data starting in 1971 or earlier and water quality data of >10 years (see Section 3.3).

In the Sava, daily streamflow data have been retrieved from the Global Runoff Data Centre (GRDC; provided by the Bundesanstalt für Gewässerkunde, BfG), the TransNational Monitoring Network (TNMN; initiated by the International Commission for the Protection of the Danube River, ICPDR) and national water agencies of the countries within the Sava (Environmental Agency of the Republic of Slovenia, ARSO, www.arso.gov.si; Hrvatske vode, www.voda.hr; and Republic Hydrometeorological Service of Serbia, www.hidmet.gov.rs). The temporal and spatial resolution and length of these time series greatly differ. Apart from Slovenia, daily streamflow data from national water agencies are barely available for more than a few years.

For the Ebro and Sava datasets, gaps of one day in daily streamflow were filled with the average of streamflow registered on the previous and following day. Gaps of more than one day were filled based on streamflow data from donor stations (i.e., "similar" stations in the dataset) according to the procedure introduced by Hughes and Smakhtin (1996). First, all stations with a Pearson's correlation above 0.8 in daily streamflow were chosen as potential donor stations for each site (López-Moreno et al., 2011). Second, monthly flow duration curves (i.e., empirical distribution functions of discharge values separated per month) were calculated for all stations. Third, gaps were filled with the streamflow value of the flow duration curve at the target station evaluated at the flow percentile value of the donor station on the respective day with missing data. As donor stations might have a gap on the same day as the respective target station, this procedure had to be repeated for all potential donor stations in descending order of the correlation coefficients until the gap was filled or all donor stations were checked. The remaining data gaps were not filled. Gap filling was not necessary for the Adige, as time series of daily streamflow were complete in the considered time frame.

For all three datasets, years with >30 values of missing daily streamflow measurements were set to years without information at the respective gauging station. This was done to ensure a minimum coverage of two months per season within each year. Subsequently, stations were excluded from the analysis if information was missing for >60% of the study period 1971–2010 (i.e., at least 16 years of record). This relatively large threshold was necessary to obtain a good spatial coverage with streamflow gauges in all basins (i.e., some of the time series in the Adige and Sava have a length of 20 years or less). This procedure resulted in a subset of 24 stations for the Adige, 41 stations for the Ebro, and 20 stations for the Sava (Fig. 2). In each river basin, sub-basins associated with the selected gauging stations were then extracted through GIS analysis using a European-wide digital elevation model provided by the GMES RDA project (EU-DEM; http://www.eea.europa.eu/data-and-maps/data/eu-dem).

3.3. Nitrate concentration data

In the Adige, nitrate concentrations in streamwater are available at 81 sampling locations at monthly resolution. Eleven gauging stations are located in the Alto Adige Province (all along the Adige main stream) and 70 stations in the Trentino Province (along both the Adige River and its tributaries, and the Noce River and its tributaries). Data are provided by the Environmental Protection Agencies of Province of Trento (http://www.appa.provincia.tn.it) and Bolzano (http://www.provincia.bz.it/agenzia-ambiente/). In the Ebro, water quality data are available for most of the 296 streamflow gauges. The temporal resolution ranges from multiple measurements per month to one sample per year. Nitrate concentrations data were extracted only for the 41 sites considered in the streamflow analysis. In the Sava, nitrate concentrations are available from the Trans-National Monitoring Network (TNMN) with a monthly time step. The TNMN was launched in 1996 to continuously measure water quality data in the Danube River Basin and also comprises 23

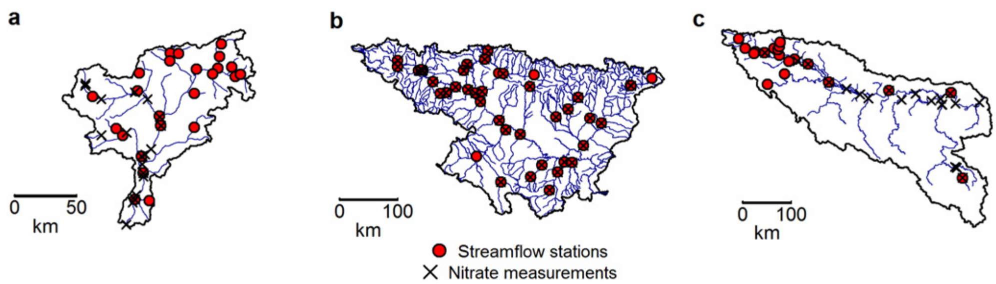

Fig. 2. Map presenting streamflow gauging stations (red dots) and water quality stations (black crosses) adopted for the trend analyses in the river basins of the (a) Adige, (b) Ebro, and (c) Sava.

stations in the Sava (data available at http://www.icpdr.org/wq-db/). Additionally, water quality data for the Sava were requested at the national water agencies (cf. Section 3.2).

In order to perform trend analyses on both concentrations and mass fluxes, we considered in all three basins only those stations with at least 30 concentration-streamflow measurements pairs during the period 1996 to 2012. Censored nitrate concentrations (i.e., values below detection limit) were discarded prior to analysis. Nitrate concentrations were associated with instantaneous measurements of streamflow at the same location if available. At the remaining locations (i.e., nitrate sampling points with neither measured nor reconstructed streamflow value on the same day; cf. Section 3.2), streamflow data were extrapolated from nearby donor gauges. Extrapolation was done by rescaling measured streamflow at the donor station by the ratio between the catchment areas of target and donor station. Nitrate concentrations without streamflow measurements at donor stations on the sampling day were discarded prior to analysis. The aforementioned procedure resulted in the selection of 19, 37 and 22 stations for the Adige, Ebro and Sava, respectively (see Fig. 2). We note that the location of the stations for water quality trends does not necessarily coincide with that adopted for the streamflow analysis.

3.4. Statistical methods

Trend analyses were performed with the nonparametric Mann-Kendall test in all river basins (MK-test; Mann, 1945; Kendall, 1975). The MK-test is applied for detection of monotonic increasing or decreasing trends and has been widely used for trend analysis of hydroclimatic time series (e.g., López-Moreno et al., 2011; Morán-Tejeda et al., 2014; Renard et al., 2008). In contrast to parametric trend tests, it does not require a priori assumptions of the underlying parameter distributions and is favourable in the analysis of multiple datasets (Hirsch et al., 1991). For the streamflow analysis, we used the R-statistics package "zyp", which implements the MK-test combined with the pre-whitening method developed by Zhang et al. (2000) and Yue et al. (2002). This method removes serial correlation prior to trend analysis to avoid erroneous trend detection due to serial correlation of the time series. Field significance of streamflow trends was assessed by the bootstrap method described in Yue et al. (2003) to test whether the number of local trends indicates the presence of a basin-wide trend. For water quality analysis, we applied the R-package "wq" water quality package. The sign and magnitude of trends was determined by Sen's slope estimator (Sen, 1968). The statistical significance of trends was defined using a significance level of $\alpha = 0.1$ for Kendall's p-value.

MK-trends were computed for the annual mean of daily mean temperature, annual precipitation, the annual mean of daily mean streamflow (Q_{Mean}), the 10- and 90-percentiles of daily streamflow extracted from the flow duration curve (i.e., Q_{10} and Q_{90}, respectively) and the annual minimum streamflow on seven consecutive days (i.e., MAM7). Streamflow trends were also correlated with sub-basin specific climate trends. To this end, the annual mean of daily mean temperature and annual precipitation totals were averaged over the drainage areas of the selected sub-basins (cf. Section 3.2) and MK-trends were computed for the resulting annual time series. We overlaid these sub-basin trend maps with those of the streamflow trends in order to highlight potential relationships and spatial correlations between climate and streamflow.

Nitrate pollution was assessed by trend analysis of nitrate concentrations, mass fluxes and flow-adjusted concentrations (FAC; Hirsch et al., 1991; Smith et al., 1982). FAC is defined as the actual concentration minus the conditional concentration (C) estimated as a function of streamflow (Q) through regression of a function $C = f(Q)$ to the concentration data. We tested several forms of $f(Q)$ (i.e., linear, logarithmic, hyperbolic and inverse), and selected the one showing the highest R^2 and the lowest probability of erroneously rejecting the null hypothesis (p) following the procedure described in Smith et al. (1982). If the relationship between C and Q was poor ($p > 0.10$) or if the number of discharge values was below 24, the estimated concentration (C) was set to the average actual concentration. FAC is supposed to filter out dilution (i.e., variability of concentration due to changes in streamflow), thereby highlighting changes in the processes that lead to contaminant input to the river (Smith et al., 1982). If the drivers of pollution have not changed over the period of record, FAC will randomly fluctuate around zero. In contrast, a new source (or elimination of a source) in the river basin might become apparent as an upward (or downward) trend in FAC. Conversely, trends in contaminant concentrations indicate how streamwater quality has evolved over the period of record, while trends in mass fluxes are a proxy of changes in emission originating from the various pollution sources and in decay rates. The three metrics for nitrate pollution (i.e., trends in concentration, mass flux and FAC) were compared to trends in monthly mean streamflow (instead of Q_{Mean}) for the same reference period between 1996 and 2012 at the associated gauging station where streamflow was available as measured or extrapolated value.

4. Results

4.1. Trends in the Adige River Basin

4.1.1. Climate

Mann-Kendall trend analysis indicates that annual temperature averages of the Adige have slightly increased between 1971 and 2010 (Fig. 3a). The annual mean of daily temperatures shows an increasing trend in more than half of the basin, yielding an increase of $+0.004$ °C y^{-1} (standard deviation of 0.03 °C y^{-1}) on average across the river basin. The largest increase (maximum positive value of $+0.091$ °C y^{-1}) has occurred in the southern part of the catchment and in the lower altitude areas (i.e., the central part of the river basin). In addition, positive significant trends have been detected in the north–east (Isarco valley). Some zones of the Adige show significant decreasing trends in mean temperature (largest decrease of -0.089 °C y^{-1}), especially in headwater catchments in the western and north–western region (upper Noce and upper Adige) and in the east (upper Avisio).

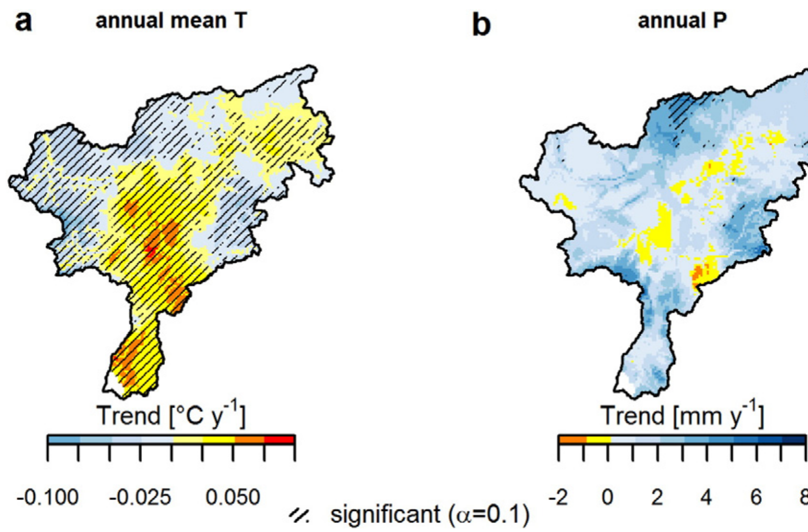

Fig. 3. Mann-Kendall trend analysis of annual mean temperature (a) and total precipitation (b) in the Adige River Basin (1971–2010). Colours show Sen's slope estimator (°C y^{-1} for temperature and mm y^{-1} for precipitation, respectively) for each grid cell (1 km regular grid). Significant trends ($\alpha = 0.1$) are shown as hatched areas.

Annual precipitation in the Adige does not show a general trend between 1971 and 2010, which results from locally divergent trends (Fig. 3b): some parts of the basin show increasing trends (i.e., mainly in the upper Passirio and Isarco valleys in the north and in the upper Noce and Avisio valleys in the middle section), whereas other areas show decreasing trends (i.e., mainly in the lower-altitude areas of Noce, Isarco and Avisio valleys in the north and centre of the Adige). The average trend in mean annual precipitation across the basin area is $+1.48$ mm y^{-1} (standard deviation of 1.15 mm y^{-1}), with a maximum of $+7.76$ mm y^{-1} and a minimum of -1.70 mm y^{-1}. While temperature trends are statistically significant in most of the basin, precipitation trends are significant in a small portion of the basin only and exclusively in areas with upwards trends (mainly in the upper Passirio and Isarco valleys).

4.1.2. Streamflow

Analysis of streamflow data at 24 stations in the Adige does not reveal a homogeneous trend pattern in annual mean streamflow (Q_{Mean}) between 1971 and 2010 (Table 1). MK-trend analysis of specific streamflow (i.e., Sen's slope per year divided by sub-basin area) detects one significant trend only (i.e., increase of 0.18 Ls^{-1} $km^{-2}y^{-1}$ in Stedileri, Leno di Terragnolo River in the southern portion of the basin; Fig. 4). Similarly, no overall trend in MAM7 becomes apparent, with four gauging stations showing a significant increase and three showing a significant reduction, respectively. The same considerations hold for the Q_{90} quantile (i.e., four positive and two negative significant trends, respectively). The only index exceeding the minimum number for field significance of the trend is Q_{10}, which exhibits a significant downward trend at five stations (21%; field significance of Q_{10} for two or more stations).

Table 1
Mann-Kendall trend analysis of streamflow data (significance level of $\alpha = 0.1$) at 24 gauging stations in the Adige River Basin (Fig. 2a) from 1971 to 2010.

	Number of trends		Number of significant ($\alpha =$ 0.1) trends	
	Increasing	Decreasing	Increasing	Decreasing
Q_{Mean}	12 (50%)	12 (50%)	1 (4%)	0 (0%)
Q_{10}	9 (38%)	15 (63%)	0 (0%)	5 (21%)
Q_{90}	11 (46%)	13 (54%)	4 (17%)	2 (8%)
MAM7[a]	13 (54%)	11 (46%)	4 (17%)	3 (13%)

[a] Annual minimum of the daily mean streamflow on seven consecutive days.

Aggregated sub-basin temperature (Fig. 4a) shows downward trends in the west and upward trends in the south and parts of the east of the Adige, respectively. Sub-basin precipitation trends (Fig. 4b) are upwards in nearly the entire basin, albeit significant in a small part only (i.e., for a tributary of the Isarco River in the north; see Fig. 1 for location of main rivers and regions in the Adige). In general, sub-basin trends of the climatic variables do not translate into significant streamflow trends. This also applies to the west of the basin, where one might expect the significant downward trends in temperature and non-significant upward trends in precipitation to result in increased streamflow. The only sub-basin that shows an increase in aggregated sub-basin temperature and a decrease in aggregated sub-basin precipitation, respectively, is the Leno tributary in the southern tip of the basin. Nonetheless, this does not result in a significant downward trend in streamflow at this station (Fig. 4). Overall, changing climate appears to have had a secondary impact on streamflow in the Adige over the studied period.

4.1.3. Nitrate pollution

In the period 1996 to 2012, annual mean nitrate concentrations in stream water ranged from 0.79 to 12.52 mg L^{-1} (mean $= 3.77$ mg L^{-1}; standard deviation $= 2.58$ mg L^{-1}) at the 19 investigated stations. Nine stations out of 19 (47%) show significant concentration trends (significance level $\alpha = 0.1$) during the investigation period (Fig. 5a). These trends are all downward and mainly occurred at locations characterized by agricultural and irrigated areas, with a minimum trend of -0.56 mg L^{-1} y^{-1} at station "valle di Lana - ponte FFSS" (located in the northern part of the basin), and a maximum of -0.032 mg L^{-1} y^{-1} at station "ponte di Borghetto" (in the southern part, at the border with the Veneto region). The decrease in nitrate concentrations for statistically significant trends averages -0.12 mg L^{-1} y^{-1}. In the same time frame, significant downward trends in monthly mean discharge can be observed for three stations only (changes ranging between -0.98 m^3s^{-1} y^{-1} and -1.09 m^3s^{-1} y^{-1}; downward pointing triangles in Fig. 5). Despite a potential reduction of dilution due to decreasing streamflow, concentration trends at these stations are, nonetheless, either downward or statistically non-significant.

Regarding mass fluxes, ten out of 19 stations (52%) show significant trends ($\alpha = 0.1$) for the period 1996 to 2012. The average annual change for these stations is $+0.28$ t d^{-1} y^{-1}, with the presence of both upward and downward trends (Fig. 5b): four stations, located in the southern part of the basin, show positive trends (maximum of $+2.64$ t d^{-1} y^{-1} at station "ponte per Villa Lagarina", Adige River in

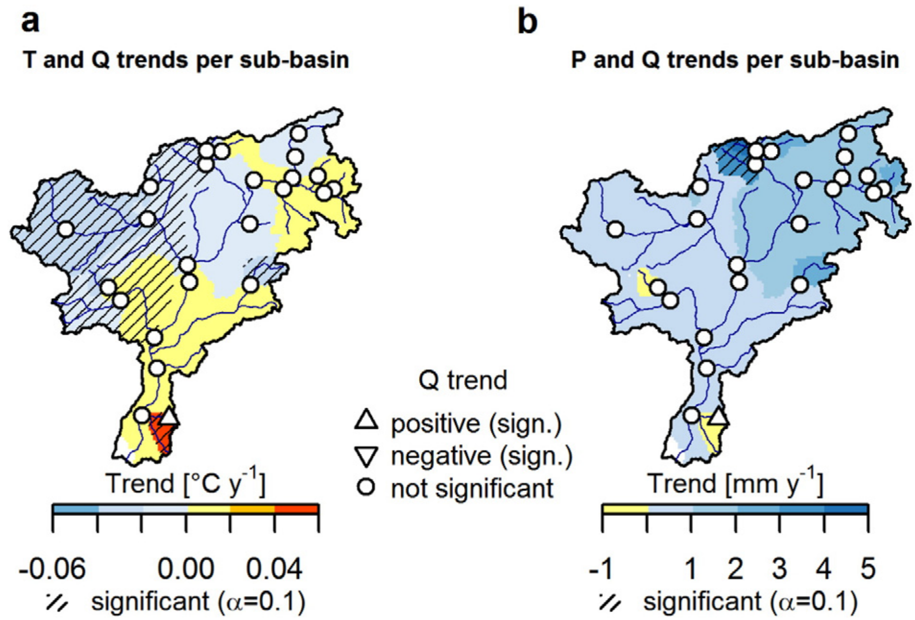

Fig. 4. Trends in annual mean streamflow (dots and triangles in both panels) and trends in (a) annual mean sub-basin temperature and (b) annual sub-basin precipitation totals in the Adige River Basin according to Mann–Kendall trend analysis (between 1971 and 2010; significance level of $\alpha = 0.1$). Significant trends in streamflow are presented as triangles (upward-pointing for upward trend and downward-pointing for downward trend) and non-significant streamflow as dots, respectively. Significant trends in sub-basin climate are shown as hatched areas.

the Trentino Province), whereas six stations show negative trends (minimum of -3.04 t d^{-1} y^{-1} at station "valle di Lana-ponte FFSS", Adige River in the Alto Adige Province). The upward trends in the southern part of the basin are likely to result from (non-significant) positive trends in the instantaneous daily discharges at these stations rather than an increase in concentrations given the downward concentration trends in this region (Fig. 5a).

The FAC trends are similar to the concentration trends: nine out of 19 stations (47%) show a significant downward trend and none of the trends is significant positive (Fig. 5c). Moreover, a mean Sen's slope of -0.26 mg L^{-1} y^{-1} in FAC (averaged over the nine significant stations) suggests decreasing nitrate pollution in the Adige. The yearly minimum and maximum values of the FAC trend are -1.80 mg L^{-1} y^{-1} and -0.03 mg L^{-1} y^{-1}, respectively; they are associated with two stations along the Adige River in the northern portion of the basin (stations "valle di Lana" and "Salorno-ponte per Rovere della Luna", respectively).

Overall, the analysis of nitrate concentrations, mass fluxes and FAC suggests a reduction of diffuse river pollution in the Adige over the study period. The comparative analysis of those variables together with streamflow (Fig. 5) shows that nitrate input in the Adige has decreased independently from streamflow over the last 30 years. As FAC filters out the impact of streamflow changes (i.e., dilution effects), a negative trend in FAC indicates a reduction of nitrate loads (cf. Section 3.4), which is likely due to improvements of local agricultural practices.

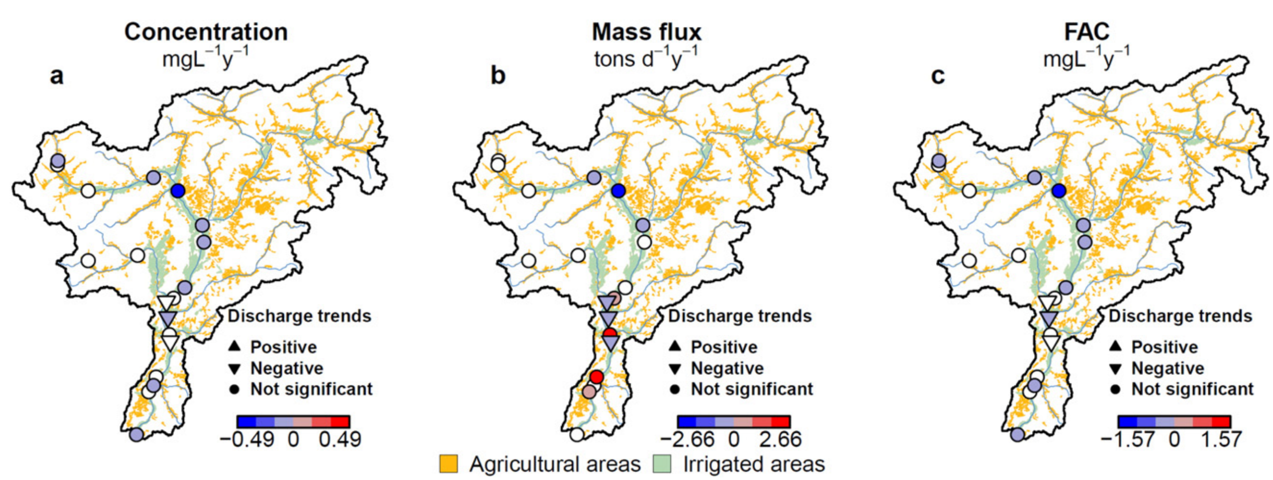

Fig. 5. Trends in (a–c) monthly mean streamflow and (a) monthly concentration, (b) monthly mass flux, and (c) FAC of nitrate in the Adige River Basin between 1996 and 2012 (significance level of $\alpha = 0.1$). Nitrate trends are indicated by colours (colour bars give the magnitude of Sen's slope value per year; white for non-significant trends); streamflow trends are indicated by triangles (upward-pointing triangles for upward streamflow trends and downward-pointing triangles for downward streamflow trends) and circles (non-significant streamflow trends). Agricultural and irrigated areas are also presented as coloured maps.

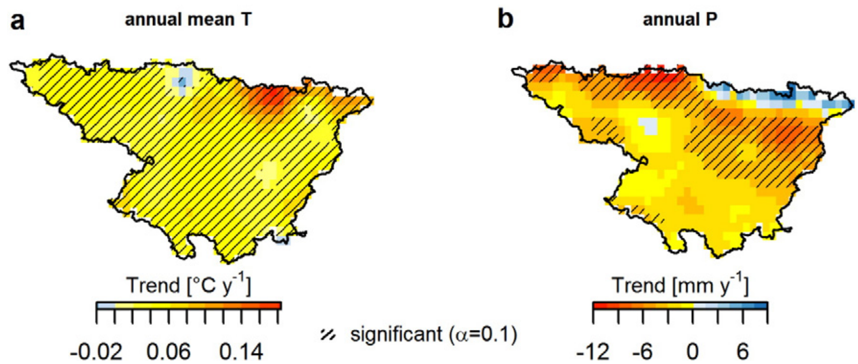

Fig. 6. Mann-Kendall trend analysis of annual mean temperature (a) and total precipitation (b) in the Ebro River Basin (1971–2007). Colours show Sen's slope estimator (°C y^{-1} for temperature and mm y^{-1} for precipitation, respectively) for each grid cell (10 × 14 km grid). Significant trends ($\alpha = 0.1$) are shown as hatched areas.

4.2. Trends in the Ebro River Basin

4.2.1. Climate

Mann-Kendall trend analysis indicates temperature increases in the Ebro during the observational period (1971–2007; Fig. 6a). More specifically, the annual mean of daily temperatures shows an increasing trend in nearly the entire basin, yielding an increase of 0.05 °C y^{-1} on average across the river basin (standard deviation of 0.03 °C y^{-1}; range of −0.02 to 0.18 °C y^{-1}). The largest increase has occurred in headwater catchments in the centre of the Eastern Pyrenees. A temperature decrease has been detected for a few cells in the Western Pyrenees and a small patch in the south-eastern tip of the basin only.

Annual precipitation in the Ebro has decreased between 1971 and 2007, with the exception of the northern fringe of the Eastern Pyrenees (Fig. 6b). Averaging over all the basin area, the trend is −3.0 mm y^{-1} (standard deviation of 2.77 mm y^{-1}; range of −11.43 to 8.84 mm y^{-1}). The decreasing trend in precipitation is significant in a wide strip from the Western Pyrenees to the northern Mediterranean fringe of the Ebro. Significant increasing trends in annual precipitation have not been detected. In view of the significant downward trends in most of the northern half of the basin, this area can be considered most prone to changes in the hydrological regime due to changing precipitation patterns and quantities. As runoff in the Ebro will increasingly rely on the Pyrenees region (López-Moreno et al., 2011), this highlights the risk of increasing water scarcity for the entire basin.

4.2.2. Streamflow

Analysis of streamflow data at 41 stations in the Ebro River Basin indicates a clear overall reduction in annual mean streamflow (Q_{Mean}) between 1971 and 2010 (Table 2). Q_{Mean} shows a significant decreasing trend at 19 out of 41 stations (46% of all stations). The change in specific streamflow at these stations is, on average, −0.25 Ls^{-1} $km^{-2}y^{-1}$, with the largest reduction (−2.12 Ls^{-1} $km^{-2}y^{-1}$) observed in Riezu (Ubagua River) in the Western Pyrenees. The analysis of quantile time series corroborates this trend towards decreasing streamflow: Q_{10} and MAM7 both show a significant decreasing trend at 16 stations (39%), and Q_{90} shows a significant negative trend at more than half of the stations (51%).

Table 2
Mann-Kendall trend analysis of streamflow data (significance level of $\alpha = 0.1$) at 41 gauging stations in the Ebro River Basin (Fig. 2b) from 1971 to 2010.

	Number of trends		Number of significant (α = 0.1) trends	
	Increasing	Decreasing	Increasing	Decreasing
Q_{Mean}	1 (2%)	40 (98%)	0 (0%)	19 (46%)
Q_{10}	3 (7%)	38 (93%)	0 (0%)	16 (39%)
Q_{90}	3 (7%)	36 (88%)[a]	1 (2%)	21 (51%)
MAM7[b]	5 (12%)	36 (88%)	1 (2%)	16 (39%)

[a] No trend detectable at two stations.
[b] Annual minimum of the daily mean streamflow on seven consecutive days.

Spatial analysis of average sub-basin temperature trends in the Ebro indicates that all sub-basins, apart from one in the Western Pyrenees, have undergone significant temperature increases (Fig. 7a). The most pronounced increase has occurred in the Eastern Pyrenees, with mean sub-basin trends ranging from 0.1 to 0.15 °C y^{-1}. In the single sub-basin where a downward (non-significant) trend in mean temperature has been observed (i.e., blue sub-basin in Fig. 7a associated with station "Liedena" at river Irati in the Western Pyrenees), streamflow still shows a significant negative trend, presumably due to a simultaneous reduction in precipitation (Fig. 7b). In 36 out of 41 sub-basins (88%), temperature trends are upward and precipitation trends downward, which underlines the risk of increasing water scarcity in the Ebro. Sub-basins in the western part of the basin appear to have undergone a more pronounced change in climate compared to sub-basins in the east, as both increasing temperature and decreasing precipitation trends are significant in this region. In the eastern part of the basin, in contrast, precipitation reductions are non-significant, and three headwaters in the Eastern Pyrenees present a positive trend. Nonetheless, streamflow has significantly decreased in these headwaters. This emphasizes the likely role of evapotranspiration in driving streamflow changes in this part of the Ebro, as (i) the precipitation increase has presumably been counterbalanced by a substantial temperature increase accompanied by enhanced evapotranspiration, and (ii) increasing forest cover following land abandonment might have further intensified evapotranspiration and rainfall interception by vegetation (Buendia et al., 2015; Gallart and Llorens, 2004).

4.2.3. Nitrate pollution

In the period 1996–2012, annual mean nitrate concentrations in streamwater ranged from 1.70 to 38.55 mg L^{-1} (mean = 9.81 mg L^{-1}; standard deviation = 8.10 mg L^{-1}) at the 37 investigated stations. Among those, 23 stations (62%) show significant concentration trends (significance level $\alpha = 0.1$) for the period 1996 to 2012 (coloured symbols in Fig. 8a). Concentrations reduced at 22 stations (minimum trend of −0.75 mg L^{-1} y^{-1} in Oron at the Oroncillo River, Humid Atlantic region; cf. Fig. 1), and increased at one site only (trend of +0.22 mg L^{-1} y^{-1} in Calamocha at the Jiloca River, Southern Mediterranean region). The mean trend for the 23 significant stations is −0.22 mg L^{-1} y^{-1}. The significant stations are all located within agricultural and irrigated areas and are distributed over all regions of the Ebro (cf. Fig. 1).

Regarding nitrate mass flux, the annual mean trend for the period 1996 to 2012 is significant for 19 out of 37 sites (51%) with an average value of −0.66 t d^{-1} y^{-1} at these sites. The significant trends are all

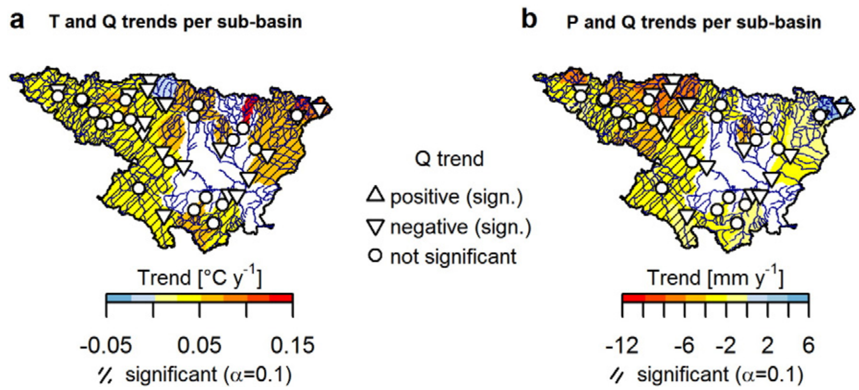

Fig. 7. Trends in annual mean streamflow (Q_{Mean} between 1971 and 2010; dots and triangles in both panels) and trends in (a) annual mean sub-basin temperature (1971 to 2007) and (b) annual sub-basin precipitation totals (1971 to 2007) in the Ebro River Basin according to Mann–Kendall trend analysis (significance level of $\alpha = 0.1$). Significant trends in streamflow are presented as triangles (upward-pointing for upward trend and downward-pointing for downward trend) and non-significant streamflow as dots, respectively. Significant trends in sub-basin climate are shown as hatched areas.

negative (Fig. 8b). Annual changes in mass flux range from -0.004 t d^{-1} y^{-1} ("Embalse de Caspe" reservoir, Guadalope River in the Southern Mediterranean region) to -5.73 t d^{-1} y^{-1} (station in Zaragoza-Monzalbarba in the middle part of the Ebro River).

The pattern of FAC trends is similar to that of concentration: 26 stations out of 37 (70%) show significant trends (Fig. 8c), among which only one is positive (station in Calamocha, Humid Atlantic region, presenting an increase of $+0.22$ mg L^{-1} y^{-1}). The station with a positive FAC trend coincides with the only station showing a positive concentration trend (Fig. 8a). The mean Sen's slope of FAC trends at all significant stations is -0.22 mg L^{-1} y^{-1} and the minimum Sen's slope is -0.50 mg L^{-1} y^{-1} (station in Arce, Zadorra River in the Humid Atlantic region).

Trends in monthly mean discharge between 1996 and 2012 range from -0.24 m^3s^{-1} y^{-1} (station in La Seu d'Urgell, Segre River in the Eastern Pyrenees) to $+0.05$ m^3s^{-1} y^{-1} (station in Calamocha, Jiloca River in the Southern Mediterranean region). Significant downward trends have been observed at 16 stations (43%) and significant upward trends have been found at 2 stations (5%). The downward trends are concentrated in the north–east, whereas the two upward trends are in the south. Despite this overall reduction in streamflow, which is associated with a decreased dilution of nitrate inputs, nitrate pollution in the Ebro has generally decreased over the last 30 years. In particular, FAC trends indicate changes in the processes that deliver nitrates to the rivers, especially in the Ebro main stem where pronounced significant downward trends in FAC were detected. The only station with an opposite pattern of nitrate trends is the station in Calamocha (Southern Mediterranean region), for which concentrations and FAC show large significant positive trends. In view of a simultaneous significant positive trend in monthly mean streamflow (leading to increased dilution), this suggests a substantial increase of nitrate input in the corresponding sub-basin over the last 15 to 20 years.

The results of this trend analysis is in contrast to previous research on seasonal trends in nitrate concentrations in the Ebro (Lassaletta et al., 2009), which suggests an overall pattern of increasing concentrations for the basin. However, we note that these previous analyses were carried out for the period 1980 to 2005. The diverging results might, therefore, be caused by a recent change in amount and application of nitrate fertilizers, which has become apparent over the last few years only.

4.3. Trends in the Sava River Basin

4.3.1. Climate

Annual mean temperature in the Sava shows a significant positive trend in the entire basin (Fig. 9a), with an average value of 0.04 °C per year across the river basin (standard deviation of 0.004 °C y^{-1}; range of 0.033 to 0.058 °C y^{-1}). Temperature has increased to a larger extent in the upstream part and east of the Sava, respectively, compared to the centre of the basin. Nonetheless, spatial differences in the magnitude of temperature changes appear to be minor.

Annual precipitation shows an overall increase (Fig. 9b), with an average of 1.57 mm y^{-1} (standard deviation of 1.48 mm y^{-1}; range of -3.00 to 12.27 mm y^{-1}). Alternating clusters of non-significant upwards and downwards trends indicate a spatially diverse pattern of annual precipitation trends especially in the Slovenian part of the basin. The headwater catchments in Slovenia show the largest downward (albeit non-significant) trends in annual precipitation. However, one grid

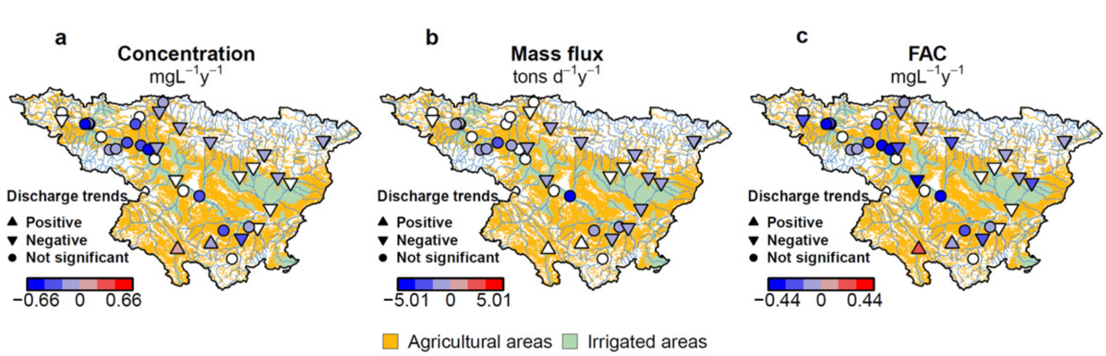

Fig. 8. Annual trends in (a–c) monthly mean streamflow and (a) monthly concentration, (b) monthly mass flux, and (c) FAC of nitrate in the Ebro River Basin between 1996 and 2012 (significance level of $\alpha = 0.1$). Nitrate trends are indicated by colours (colour bars give the magnitude of Sen's slope value per year; white for non-significant trends); streamflow trends are indicated by triangles (upward-pointing triangles for upward streamflow trends and downward-pointing triangles for downward streamflow trends) and circles (non-significant streamflow trends). Agricultural and irrigated areas are also presented as coloured maps.

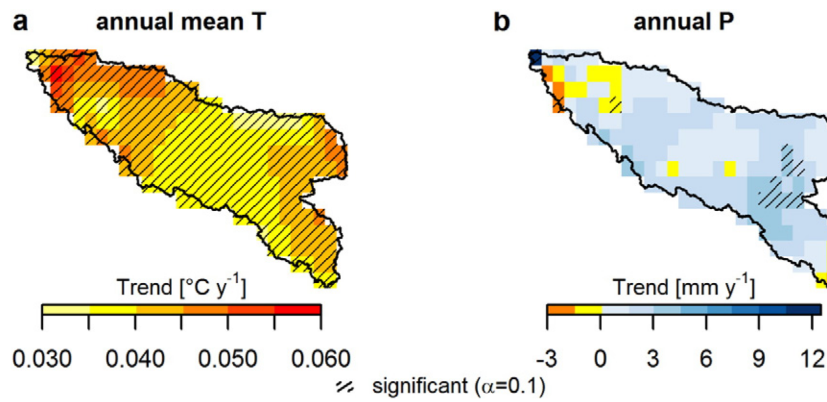

Fig. 9. Mann-Kendall trend analysis of annual mean temperature (a) and total precipitation (b) in the Sava River Basin (1971–2010). Colours show Sen's slope estimator (°C y^{-1} for temperature and mm y^{-1} for precipitation, respectively) for each grid cell (20 × 27.5 km grid). Significant trends ($\alpha = 0.1$) are shown as hatched areas.

cell in the most western tip of the basin shows an opposite trend with a large precipitation increase of 12.27 mm y^{-1}. Significant trends are restricted to small patches in the western zones (i.e., downward trends in Slovenia and Croatia) and eastern zones of the basin (i.e., upward trends in Bosnia and Herzegovina and Serbia), respectively.

4.3.2. Streamflow

Annual mean streamflow has significantly decreased at half of the gauging stations, whereas no significant increasing trends have been identified in the Sava. In terms of change in specific streamflow, this corresponds to a mean change of -0.13 Ls^{-1} $km^{-2}y^{-1}$ at the significant stations, ranging from -0.19 Ls^{-1} $km^{-2}y^{-1}$ to -0.06 Ls^{-1} $km^{-2}y^{-1}$ (Slovenian stations Radece and Podbocje, respectively). This indicates an overall trend towards diminishing streamflow, which is also suggested by trend analysis of low-flow and high-flow indices (Table 3). The reduction in streamflow appears to be more severe during low-flow compared to high-flow periods, as trends are significant negative at 30% of all stations for the low-flow indices (i.e., Q_{90} and MAM7), and at 10% of all stations for the high-flow index Q_{10}. The amount of significant decreasing trends is field-significant for all indices according to the bootstrap method (Yue et al., 2003), which confirms the tendency towards declining streamflow in the Sava.

Both temperature and precipitation trends are upward in all investigated sub-basins (Fig. 10). However, significant downward streamflow trends have only been identified in the headwaters in Slovenia, whereas streamflow trends are non-significant further downstream. In the Slovenian headwaters, temperature increases have been more severe (Fig. 10a), which suggests increasing temperatures and thus enhanced evapotranspiration as likely main drivers for the observed negative streamflow trends. Further downstream, on the contrary, temperature increases are less pronounced, whereas precipitation increases become larger (albeit the precipitation trends are not statistically significant). This might indicate that enhanced evapotranspiration has been counterbalanced by the precipitation surplus in this part of the Sava, which would explain the absence of significant streamflow trends downstream of the Slovenian headwaters. However, in contrast to the Slovenian part of the basin, streamflow data were analysed at a few locations only (mostly along the main stem of the Sava river). Hence, it was not possible to study streamflow trends in headwater catchments in the middle and downstream section of the basin.

Table 3
Mann-Kendall trend analysis of daily streamflow data (significance level of $\alpha = 0.1$) at 20 gauging stations in the Sava River Basin (Fig. 2c) from 1971 to 2010.

	Number of trends		Number of significant ($\alpha =$ 0.1) trends	
	Increasing	Decreasing	Increasing	Decreasing
Q_{Mean}	2 (10%)	18 (90%)	0 (0%)	10 (50%)
Q_{10}	3 (15%)	17 (85%)	0 (0%)	2 (10%)
Q_{90}	4 (20%)	16 (80%)	1 (5%)	6 (30%)
MAM7[a]	6 (30%)	14 (70%)	1 (5%)	6 (30%)

[a] Annual minimum of the daily mean streamflow on seven consecutive days.

4.3.3. Nitrate pollution

Annual mean nitrate concentrations range between 1.89 mg L^{-1} and 8.25 mg L^{-1} at all analysed stations ($n = 22$; mean = 4.68 mg L^{-1}; standard deviation = 1.63 mg L^{-1}) for the period 1996 to 2012. Among those, 13 stations (59%) show significant concentration trends (significance level $\alpha = 0.1$), with all but one being downward (Fig. 11a). The most pronounced decreasing trend occurs at station Litija in Slovenia (-0.66 mg L^{-1} y^{-1}). The only station with a significant positive trend is in Modrica at the Bosna River with a Sen's slope of $+0.45$ mg L^{-1} y^{-1}. The mean of Sen's slope at all significant stations is -0.15 mg L^{-1} y^{-1}, which is consistent with Vrzel and Ogrinc (2015) who report mostly decreasing nutrient concentrations at eight stations along the Sava River in recent years.

Regarding mass flux, seven stations out of 22 (31%) show a significant trend ($\alpha = 0.1$) for the period 1996 to 2012 (Fig. 11b). The significant trends are exclusively downward (Fig. 11b), with a mean value of -15.41 t d^{-1} y^{-1} and a range between -2.29 t d^{-1} y^{-1} (station in Jesenice, Sava River, at the border between Slovenia and Croatia) and -31.16 t d^{-1} y^{-1} (most downstream station in Ostruznica, Serbia, at the Sava River). Considering FAC trends, we see a similar pattern as for the concentration trends: twelve stations out of 22 (56%) show significant trends (Fig. 11c), of which only one is upward (station in Modrica; Sen's slope of $+0.45$ mg L^{-1}). The minimum Sen's slope is -0.49 mg L^{-1} y^{-1} (station Litija) and the mean Sen's slope at all significant stations is -0.14 mg L^{-1} y^{-1}.

The comparative analysis of the three variables related to nitrate pollution (i.e., concentration, mass flux, and FAC) shows that nitrate input in the Sava catchment has been reduced in the last 30 years. Moreover, whereas anthropogenic pollution particularly affects the lower reaches of the Sava River (Markovics et al., 2010), this does not seem to hold for nitrate pollution, as the trends in the considered variables are downward also in the middle and lower section of the basin. The only exception is the station in Modrica (Bosna River), for which concentration and FAC trends are positive significant and thus indicate an increase of nitrate loads (see Section 3.4).

Trends in monthly aggregated streamflow are mostly non-significant apart from the stations Badovinci (Drina River; trend of $+3.76$ m^3 s^{-1} y^{-1}) and Litija (Sava River; trend of $+3.10$ m^3 s^{-1} y^{-1}). The latter station shows the most substantial reduction in both concentrations and FAC among the investigated stations. With a significant downward trend in FAC, this cannot only result from a streamflow increase, but also from a reduction in nitrate input into

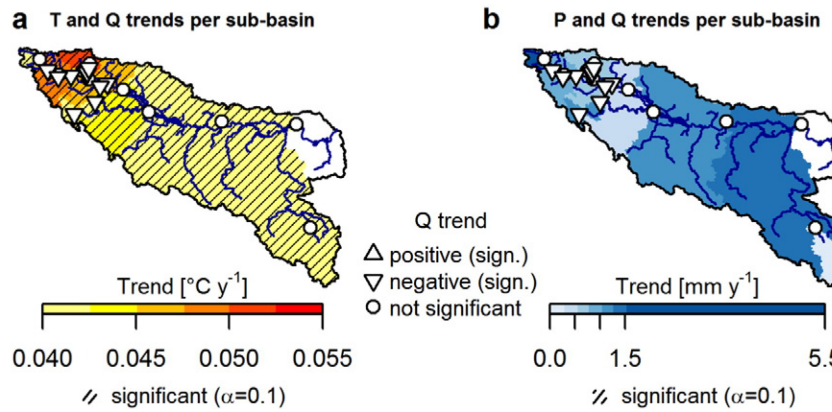

Fig. 10. Trends in annual mean streamflow (Q; dots in both panels) with trends in (a) annual mean sub-basin temperature (T) and (b) annual sub-basin precipitation totals (P) in the Sava River Basin according to Mann–Kendall trend analysis (between 1971 and 2010; significance level of $\alpha = 0.1$).

the river. Due to the absence of significant streamflow trends at most measurement points, it was not possible to further compare streamflow to nitrate concentration and mass flux. To test whether the monthly aggregation might mask significant streamflow trends between 1996 and 2012, we also considered streamflow trends in the annual mean of daily streamflow (Q_{Mean}). This did not show any significant streamflow trends at the sites with nitrate measurements, as opposed to the analysis of the period from 1971 to 2010 (cf. Section 4.3.2). Hence, this suggests that the short time frame of 17 years, rather than the monthly aggregation of streamflow, is the main reason for the small number of significant streamflow trends in this analysis.

5. Discussion

5.1. Climate

In general, all three basins exhibit increasing temperatures from 1971 onward. However, the magnitude of the average increase is much lower in the Adige (+0.004 °C y^{-1}) compared to the Ebro (0.05 °C y^{-1}) and Sava (0.04 °C y^{-1}), respectively. Moreover, areas with significant temperature reduction can be found in the Adige (Fig. 3a), which are not present in the other catchments (Figs. 6a and 9a, respectively). Local climate trends can become smoothed or even filtered out with grid coarsening, which might explain the small spatial variability of trends in the Sava (standard deviation of 0.004 °C y^{-1}) compared to the other two basins (standard deviation of 0.03 °C y^{-1} in both). Nonetheless, it becomes apparent from this analysis that Ebro and Sava are at much higher risk of rising temperatures in the coming years than the Adige. This agrees with climate projections for the Alpine region, which generally show moderate temperature increases for the first half of this century, followed by more pronounced increases during the second half (Gobiet et al., 2014). The only region in the Adige prone to significant temperature increases in the near future might be the southern part, where droughts (especially in summer) have become more frequent in recent years (Chiogna et al., 2016).

As opposed to temperature trends, precipitation trends appear to be more consistent for the Adige and Sava compared to the Ebro. Both the Adige and Sava show net increases in precipitation (1.48 mm y^{-1} and 1.57 mm y^{-1}, respectively), whereas the Ebro shows a net reduction (−3.0 mm y^{-1}). With the eastern fringe of the Pyrenees being an area of upward trends as opposed to the rest of the basin, the Ebro shows the largest standard deviation in total precipitation changes (standard deviation of 2.77 mm y^{-1} versus 1.15 mm y^{-1} in the Adige and 1.48 mm y^{-1} in the Sava, respectively). The contrasting precipitation trends among the study basins are likely related to their geographical location, as the transition zone between increasing and decreasing precipitation projected for the course of the 21st century crosses the Alpine region (Gobiet et al., 2014). Correspondingly, the most severe precipitation decrease by the end of this century is expected for the western and eastern part of the Mediterranean, whereas the Alps are likely to mitigate the precipitation decline to some extent (Giorgi and Lionello, 2008). This would also be consistent with projections for the

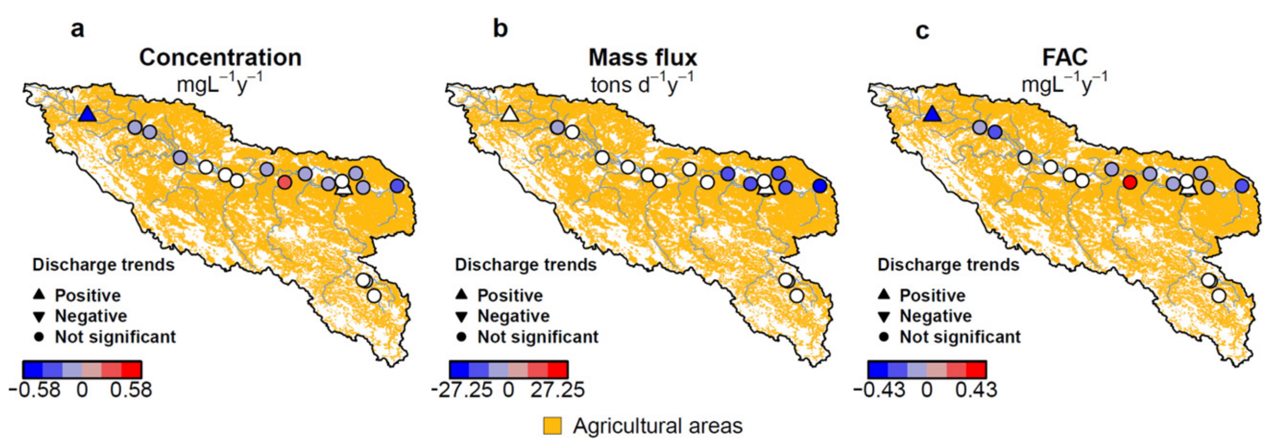

Fig. 11. Annual trends in (a–c) monthly mean streamflow and (a) monthly concentration, (b) monthly mass flux, and (c) FAC of nitrate in the Sava River Basin between 1996 and 2012 (significance level of $\alpha = 0.1$). Nitrate trends are indicated by colours (colour bars give the magnitude of Sen's slope value per year; white for non-significant trends); streamflow trends are indicated by triangles (upward-pointing triangles for upward streamflow trends and downward-pointing triangles for downward streamflow trends) and circles (non-significant streamflow trends). Agricultural areas are also presented as coloured maps.

period 2071 to 2100 that suggest secondary changes in total annual precipitation for both northern Italy and the northern Balkan region (Philandras et al., 2011).

Based on these analyses, the Ebro has to be considered the most vulnerable to changing climate among the investigated river basins: a reduction in precipitation has been accompanied by rising temperatures, which may cause enhanced evapotranspiration and thus decreasing water resources, even though this effect might be mitigated by decreased soil moisture. In contrast, the Adige seems the least affected by changing climate, as mean temperature shows a minor increase, and precipitation a slight increase rather than a reduction across the basin.

5.2. Streamflow

In the period 1971 to 2010, specific streamflow shows decreasing trends in both the Ebro and Sava, with averages of $-0.25\ Ls^{-1}\ km^{-2}y^{-1}$ and $-0.13\ Ls^{-1}\ km^{-2}y^{-1}$, respectively. On the contrary, the only significant streamflow trend in the Adige is positive (i.e., $0.18\ Ls^{-1}\ km^{-2}y^{-1}$ in Stedileri in the southern part of the basin). This confirms the findings of the climate-trends analysis in the sense that the Ebro is at highest risk of water scarcity among the investigated river basins. An overall trend towards decreasing streamflow becomes also apparent in the Sava, albeit less severe than in the Ebro. In contrast, the Adige does not show a general decline in streamflow over the study period and might, therefore, not be threatened by water scarcity in the near future. In our analysis, Q_{10} is the only parameter showing a field-significant trend across the Adige (i.e., absence of significant increasing trend, but significant decreasing trends at 21% of the stations). This might result from changes in the regulation of storage reservoirs, which include priority, flood and drought management rules (Gumiero et al., 2009). In contrast to the Adige, the number of stations with significant decreasing trends in the Ebro is similar for the analysed low-flow and high flow indices. This suggests that streamflow trends in the Ebro are mainly climate-driven and, therefore, reflected in a decline in all analysed streamflow indices, whereas streamflow trends in the Adige are likely to be driven by both climatic and anthropogenic factors (i.e., flow alteration caused by hydropower plants with reservoirs).

The largest changes in specific streamflow are observed in headwaters of the Pyrenees in the Ebro and in the upstream reaches of the Sava River in Slovenia. Such a correlation between elevation and magnitude of streamflow trends does not apply to the Adige, where streamflow trends are generally minor. Considering links between altitude, temperature, rainfall, snowfall, glacier melt and snowmelt, the larger magnitude of trends in the headwaters of the Ebro and Sava suggests that mountainous headwater catchments show low resilience to climate changes. This is consistent with climate projections for the Greater Alpine Region, which indicate that high-elevation catchments dominated by glacier and snow melt will be most affected by increasing temperatures, particularly in the second half of the 21st century (Bavay et al., 2013). In this perspective, all three investigated basins might be subject to streamflow changes associated with earlier snowmelt or increasing rainfall relative to snowfall (López-Moreno et al., 2011). Such shifts in snowmelt timing or the rainfall to snowfall ratio due to increasing temperatures have been observed for mountainous catchments in western Austria between 1980 and 2010 (Kormann et al., 2015). This is expected to affect hydropower production, which is likely to decrease throughout the 21st century and has to be adapted to changing hydrologic regimes in Alpine regions (Finger et al., 2012; Gaudard et al., 2013; Majone et al., 2016). Changes in snowfall and snowmelt regimes might, therefore, be a major driver of future changes of streamflow in the Adige and the mountainous parts of Sava, as well as in headwater catchments in the Pyrenees in the Ebro. Nonetheless, future trends in seasonal streamflow might greatly differ among mountainous catchments depending on the predominant hydrological regime in the respective catchment (e.g., glacial regimes, snowmelt regimes or snowmelt-rainfall regimes; Bard et al., 2015). Hence, the northern and central portions of the Adige may buffer the effects of changing climate by, for example, shifting from glacio-nival to nival regimes as projected for the Noce tributary (Majone et al., 2016). In the absence of such mitigating regime shifts, changes in the Pyrenees or the upstream part of the Sava might thus be much more dramatic (as also suggested by the streamflow trends analysed in this study).

Apart from the evident influence of changing climate, streamflow reduction in the Ebro might have been intensified by other anthropogenic impacts such as flow alteration by reservoirs (Batalla et al., 2004), water consumption for irrigation (Sabater et al., 2009) and increasing forest cover due to abandonment of agricultural land (Buendia et al., 2015; Gallart and Llorens, 2004). Indeed, land abandonment in the Ebro associated with increasing forest cover has started in the late 1980s (Buendia et al., 2015) and might thus have contributed to the decreasing streamflow trend between 1971 and 2010. Land use change with feedback on, particularly, streamwater quality has also occurred in the Sava due to political and economic changes after 1990 (Vrzel and Ogrinc, 2015). In the Adige, on the contrary, there is no evidence for major land use changes and ensuing streamflow alteration. The impact of those anthropogenic influences on streamwater quantity and quality can only be assessed in a more detailed analysis of, among others, land use change, hydrological alteration by damming, and seasonal streamflow indices. While such analyses are beyond the scope of this paper, the role of changing climate as major driver of change has become apparent, particularly as streamflow trends proved to be more significant in the basins with distinct climate trends (i.e., Ebro and Sava).

5.3. Nitrate pollution

In general, nitrate pollution has decreased in all investigated basins between 1996 and 2012. The largest concentration decrease has occurred in the Ebro (average of $-0.22\ mg\ L^{-1}\ y^{-1}$ for significant trends), followed by the Sava and Adige ($-0.15\ mg\ L^{-1}\ y^{-1}$ and $-0.12\ mg\ L^{-1}\ y^{-1}$, respectively). The Ebro and Sava show clear decreasing trends in all indices (i.e., concentration, mass flux and FAC). Overall concentration and FAC trends are also downward in the Adige, but mass flux trends do not show a distinct general pattern. This is correlated with some stations presenting upward streamflow trends in the Adige, which result in increasing trends of nitrate mass flux despite the downward FAC trend suggesting a reduction of nitrate input loads. Such a feedback between streamflow and mass flux is unlikely for both Ebro and Sava, as long-term streamflow trends are downward at most stations in these basins (see above). Hence, the example of diverging concentration and mass flux trends in the Adige illustrates that future pollution can be best assessed by considering not only concentration trends, but also trends in mass flux and flow-adjusted concentrations as well as streamflow. The FAC analysis allowed filtering out the effect of dilution on nitrate concentration, and the resulting trends can be attributed to changes in nutrients loads from agriculture and WWTPs.

CORINE land cover data do not suggest relevant changes in land cover in any of the basins between 1990 and 2006. Hence, a reduction of agricultural land might not be the governing factor in the decrease of nitrate pollution in the study basins. Instead, both improvements in agricultural practices and sewage treatment might have resulted in a net decrease in nitrate input, which has also been suggested in previous studies in the Adige and Ebro (Aguilera et al., 2015; Lassaletta et al., 2009; Provincia Autonoma di Trento, 2015). Such improvements are associated with the implementation of EU-wide regulations such as the Nitrates Directive or the Urban WasteWater Treatment Directive (Bouraoui and Grizzetti, 2011). In the case of the Ebro, a decline in fertilizer consumption in Spain from 2003 on (Food and Agriculture Organization of the United Nations, 2015) might have fostered the decline in nitrate emissions. This might be comparable to the situation in the Sava, where the abandonment of market regulations has increased the price of agricultural products and, consequently, caused farmers to use less fertilizer (Vrzel and Ogrinc, 2015). As a side comment, we note that the Sava shows large differences in the extent of waste water treatment among countries (e.g., 68% of agglomerations in Serbia versus 26% in Slovenia without wastewater treatment; ISRBC, 2013). While wastewater treatment plants are not the main source of nitrate input, they should be considered in the assessment of trends associated with point-source pollutants such as personal care products or pharmaceuticals.

Overall, the analysis of recent trends in nitrate pollution suggests that diffuse pollution from agriculture might not play a major role in the near future. However, rising temperatures in the next decade are likely to entail expansion of irrigated arable land. As irrigated arable land is a major source of diffuse nitrate input via irrigation return flow (Aguilera et al., 2015; Torrecilla et al., 2005), this could, in turn, lead to a reversal of the downward trend in diffuse nitrate pollution. This might, in particular, hold for the Ebro, where the fraction of irrigated arable land is considerable (especially in the valley of the Ebro River) and where climate change might be most severe in the future.

6. Conclusions

This paper presents the analysis of recent hydroclimatic and nitrate trends in three Mediterranean river basins (i.e., the river basins of the Adige, Ebro and Sava) aimed at (i) determining the most pronounced trends, (ii) identifying the potential drivers of change in each river basin and (iii) comparing the study basins with respect to their resilience to the identified drivers of change. The trend analyses indicate substantial changes in climate and streamflow especially in the Ebro, which suggests that this semi-arid river basin is at risk of severe water scarcity due to changing climate. In contrast, the results of the trend analyses do not point to diminishing water resources in the alpine Adige. With an alpine flow regime in the upper part and a continental flow regime downstream, the Sava shows characteristics similar to both the Adige and Ebro. This is also reflected in its intermediate resilience to hydroclimatic changes. Overall, these findings suggest that Mediterranean catchments are prone to drier climate and declining water resources apart from the alpine catchments in the north of the Mediterranean region, where evaporative losses due to higher temperatures are less severe and might be counterbalanced by increased precipitation.

This study has focussed on patters of annual trends, whereas some stressors on aquatic ecosystems might become apparent only at sub-annual scale. For example, storage reservoirs induce hydrological alteration in all study basins, which could not be specifically studied at annual scale. Future studies might, therefore, aim at characterizing trends over the Mediterranean at seasonal scale, taking into account more specifically the management and impact of reservoirs. Nonetheless, knowledge of hydroclimatic trends on the annual scale still allows for inferences on the impact of additional anthropogenic stressors. Such an inference can be made for the role of reservoirs, which is likely to increase in view of drier climate and the associated need for water provisioning. This might, in particular, apply to the Ebro and Sava, where streamflow has significantly decreased over the last 40 years.

Recent trends in nitrate pollution suggest that diffuse pollution has declined in all study basins. However, this trend might be reversed in the future as drier climate presumably requires increased irrigation of arable land. Similar to nitrate, increased irrigation return flow might also lead to larger input loads of other diffuse pollutants such as pesticides. Future work might thus consider other compounds as indicators for diffuse pollution, or study point pollution in different Mediterranean river basins.

To summarize, recent hydroclimatic trends emphasize the need for adapted river management in the Mediterranean region, where the significant drivers of change in addition to changing climate are (i) water demand and pollution associated with the agricultural sector and (ii) streamflow alteration induced by damming of rivers for water supply and hydropower generation. Measures of adapted river management could, for example, include a reduction in the cultivation of certain crops that are characterized by high water demand (e.g., sugar beet, lucerne, corn or rice), or changing management strategies of reservoirs to minimize the adverse effects of hydro- and thermo-peaking on aquatic ecosystems, such as drifting of aquatic organisms and disturbance of spawning in downstream reaches, or release of anoxic water from thermally stratified reservoirs (Bunn and Arthington, 2002; Prats et al., 2011).

Acknowledgements

This research has been financially supported by the European Union under the Seventh Framework Programme (Grant agreement no. 603629-ENV-2013-6.2.1-Globaqua). We thank the reviewers for their thorough comments. We also thank the Spanish Meteorological Agency (AEMET) and University of Cantabria (UC) for the data provided for this work (Spain02 dataset, http://www.meteo.unican.es/datasets/spain02). We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu). We would also like to acknowledge the Confederación Hidrográfica del Ebro (CHE) (http://www.chebro.es/), the International Commission for the Protection of the Danube River (ICPDR; https://www.icpdr.org), the Environmental Agency of the Republic of Slovenia (www.arso.gov.si), the Croatian water agency Hrvatske vode (www.voda.hr), and the Republic Hydrometeorological Service of Serbia (www.hidmet.gov.rs) for providing data for this study. We also thank the Environmental Protection Agencies and Hydrological and Meteorological Offices of the Autonomous Provinces of Trento and Bolzano for data provision in the Adige. The digital elevation model used in this study was produced using Copernicus data and information funded by the European Union (EU-DEM layers).

Appendix A. Supplementary data

Supplementary data to this article report the name, location and source of temperature, precipitation, streamflow and nitrate concentration data for this study. Supplementary data associated with this article can be found in the online version, at doi:http://dx.doi.org/10.1016/j.scitotenv.2016.07.102.

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