MEDITERRANEAN ACTION PLAN

Meeting of MED POL Focal Points
Barcelona (Spain), 18-21 June 2013

Report of nutrient riverine inputs

Delegates are kindly requested to bring their documents to the meeting
Rivers of the Mediterranean Sea: Water discharge and nutrient fluxes

Olivier MONTREUIL & Wolfgang LUDWIG
2013
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Figure 1 Major sub-basins of the Mediterranean Sea

Table 1 Major sub-basins of the Mediterranean Sea

<table>
<thead>
<tr>
<th>Basin</th>
<th>Code</th>
<th>Area (10^3 km^2)</th>
<th>Bordering countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alboran</td>
<td>ALB</td>
<td>76</td>
<td>Spain, Morocco, Algeria</td>
</tr>
<tr>
<td>North-Western</td>
<td>NEW</td>
<td>252</td>
<td>Spain, France, Monaco, Italy</td>
</tr>
<tr>
<td>South-Western</td>
<td>SWE</td>
<td>270</td>
<td>Spain, Italy, Algeria, Tunisia</td>
</tr>
<tr>
<td>Tyrrenian</td>
<td>TYR</td>
<td>242</td>
<td>Italy, France, Tunisia</td>
</tr>
<tr>
<td>Ionian</td>
<td>ION</td>
<td>184</td>
<td>Italy, Croatia, Albania</td>
</tr>
<tr>
<td>Central</td>
<td>CEN</td>
<td>606</td>
<td>Italy, Tunisia, Libya, Malta</td>
</tr>
<tr>
<td>Aegean</td>
<td>AEG</td>
<td>202</td>
<td>Greece, Turkey</td>
</tr>
<tr>
<td>North-Levantine</td>
<td>NLE</td>
<td>111</td>
<td>Turkey, Cyprus, Syria, Lebanon</td>
</tr>
<tr>
<td>South-Levantine</td>
<td>SLE</td>
<td>436</td>
<td>Lebanon, Israel, Egypt, Libya</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Source</th>
<th>Nitrogen (10^3 tN)</th>
<th>Phosphorus (10^3 tP)</th>
<th>Water (km^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>1140:1335 (1,3)</td>
<td>65 (1)</td>
<td>825:1485 (2, 4, 5, 6)</td>
</tr>
<tr>
<td>River</td>
<td>1285 (7)</td>
<td>126 (7)</td>
<td>340:347 (2,7)</td>
</tr>
<tr>
<td>Atlantic</td>
<td>-3135:-1080 (8,9)</td>
<td>-242:-38 (8, 9)</td>
<td>925 :1578 (2, 4, 10, 11, 12)</td>
</tr>
<tr>
<td>Black Sea</td>
<td>120:130 (13, 16)</td>
<td>2 (13)</td>
<td>197:311 (14, 15, 19)</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td></td>
<td></td>
<td>2300:2922 (2, 4, 5, 6)</td>
</tr>
<tr>
<td>Point source</td>
<td>285 (17)</td>
<td>74 (17)</td>
<td></td>
</tr>
<tr>
<td>Groundwater</td>
<td></td>
<td></td>
<td>50 (18)</td>
</tr>
</tbody>
</table>
Chapter 1 - Introduction

The Mediterranean Sea covers about 2.5 $10^6$ km$^2$, with an average water depth of about 1.5 km. It is commonly divided into ten sub-basins, which are shown in Figure 1 and listed in Table 1. Nitrogen, phosphorus, and silicon are crucial elements for maintaining biological productivity in the sea. In the Mediterranean as a whole, concentrations and stocks of these elements are controlled by the exchange through the Straits of Gibraltar and Bosphorus, by atmospheric deposition, by river and groundwater discharge, and by anthropogenic point sources. Nutrient fluxes into and out of the Mediterranean are strongly controlled by the associated water fluxes. By far the greatest exchange rates are observed in the Strait of Gibraltar, where nutrient-depleted Atlantic surface water enters the basin and nutrient-enriched Mediterranean deep water is exported to the open ocean. Imbalance between both creates a large nutrient deficit which is mainly responsible for the oligotrophic character of the Mediterranean Sea. In Error! Reference source not found., we list the major water and nutrient fluxes into and out of the basin. River water discharge from land to sea accounts only for one-tenth of the total water input to the Mediterranean Sea which is about 2.5 $10^3$ km$^3$ yr$^{-1}$. Despite this low river water discharge, rivers account for a large part of nutrients inputs: about 50% for nitrogen and two thirds for phosphorus.

The general objective of the work of CEFREM is to develop a database and GIS based modeling tool for the assessment of nutrient inputs into the Mediterranean Sea from rivers. Rivers are major pathways for transport of nutrients from terrestrial/anthropogenic sources to the Sea, and this work is focusing on riverine inputs. River basins integrate the variety of natural and anthropogenic sources that release nutrients (i.e., relevant elements that are necessary to maintain biological productivity) to surface waters, which may successively be transported to the river mouths and hence integrates the marine realm. It is in this sense that rivers can be considered as diffuse nutrient sources to the Sea, not in the sense that point sources (such as urban waste water releases) within the river basins are excluded. At the scale of the entire Mediterranean, diffuse sources from rivers can be opposed to point sources being direct injections of nutrients from industries and/or big cities along the coastlines. As for atmospheric depositions, these direct nutrient inputs are not considered in the present work.
Chapter 2 - Data availability for freshwater discharge and nutrient concentrations

Creation of a data base on Mediterranean rivers has already been started in the framework of a previous collaboration with MEDPOL (UNEP/MAP/MED POL 2003) and further enlarged via the European integrated research project SESAME (http://www.sesame-ip.eu/). As part of this present RFP, a new and important effort has been made to update the database through:

- screening of the recent scientific literature and existing up-to-date databases

- adding of data for sub-catchments of river basins

- adding of information for each basin and sub-catchment on potential controlling factors of river nutrient fluxes (climate, topography, lithology, land use/land cover and human activities and infrastructures).

The database we created is hence a mixture from different data sources. Not all of these data have been released to the public domain; some of them were linked to bilateral agreement between the data owners and CEFREM (Centre de Formation de Recherche sur les environnements méditerranéens), and their further use by third parties needs establishment of individual agreements too. One of our aims is therefore to use this data compilation through reprocessing and statistical analyses (modeling) for the creation of derivation data sets which could then be properly linked to our GIS on Mediterranean rivers, freely available to all end-users.

2.1 Scientific literature

Recent water-quality and discharge data series were collected through a screening of scientific literature in order to compile up-to-date information that has been acquired through independent research activities. Table 3 lists the corresponding references (not exhaustive), which are continually updated. Also information and synthesis on factors potentially controlling the spatial and temporal variation of nutrients and water discharge were included in this screening, as well as information on modeling algorithms involving this information. Scientific studies often only allow a punctual and short time view of riverine nutrient concentrations and water and material transfer to the sea, but they are generally more detailed in speciation of different nutrient forms and processes that control their mobilization. In this sense, they are highly complementary to data which have been collected through (public) monitoring networks, as they can help for data quality assessment.
<table>
<thead>
<tr>
<th>Data</th>
<th>Spatial extend</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient concentration</td>
<td>Local to regional</td>
<td>Bouza-Deano et al., 2008; Cozzi &amp; Giani, 2011; de Wit &amp; Bendoricchio, 2001; Elewa, 2010; Garcia-Esteves et al., 2007; Karageorgis et al., 2003; Koçak et al. 2010; Lassaletta et al., 2009; Lopez-Moreno et al. 2011; Moran-Tejeda et al., 2011; Moutin et al., 1998; Naldi et al., 2010; Nikolaidis et al., 2007; Oczkowski &amp; Nixon, 2008; Skoulidakis et al., 1998; Skoulidakis 2002, 2009; Snoussi et al., 2002</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>Ludwig et al., 2009, 2010,</td>
<td></td>
</tr>
<tr>
<td>World</td>
<td>Meybeck &amp; Ragu, 1997</td>
<td></td>
</tr>
<tr>
<td>Water discharge</td>
<td>Local to regional</td>
<td>Arnell, 1999; Bellos et al., 2004; Cigizoglu et al., 2004; Genev, 2003; Giakoumakis &amp; Baloutsos 1997; Huss, 2011; Kahya &amp; Kalayci, 2004; Kuhn et al., 2011; Lorenzo-Lacruz et al., 2011; Lespinas et al., 2010; Ludwig et al., 2004; Meddi &amp; Hubert, 2003; Mimides et al., 2007; Oueslati et al., 2011; Quintana-Segui et al., 2011; Rees et al., 1997; Senatore et al., 2011; Shorthouse &amp; Arnell 1997; Stahl et al., 2010; Touazi &amp; Laborde, 2004; Zanchettin et al., 2008</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>Boukthir &amp; Barnier, 2000s; Chenoweth et al., 2011; Cudennec et al., 2007; Garcia-Ruiz et al., 2011; Gao &amp; Giorgi, 2008; Struglia et al., 2004</td>
<td></td>
</tr>
</tbody>
</table>
and identification of major gaps in these networks. Synthesis studies are the basis for large scale extrapolations and trend evaluations.

2.2 Public databases

2.2.1 Nutrient concentrations

The Waterbase-rivers dataset (European Environment Agency, http://www.eea.europa.eu/data-and-maps/data/waterbase-rivers-8) contains data on nutrients in water of the WISE-SoE river monitoring stations for all European countries. These data have been assembled from national monitoring programs; they were supplied to EEA through political agreement between EU and associated member states. Alone, it allows a good spatial coverage of nutrient concentrations data in rivers of the Northern Mediterranean sea from the 2000s. This dataset will be regularly updated (last update in 2012). However, the time range of data series is highly variable between countries and rivers of each country.


The OECD Environmental Data Compendium dataset (Organization for Economic Co-operation and Development (http://www.oecd.org/env/environmentalindicatorsmodellingandoutlooks) included time series for some major rivers of the Mediterranean Sea from 1980 to 2004. It helps completing series for some rivers of Italy, Greece and one Turkish River.

2.2.2 Water discharge

The "Global Runoff Data Center" datasets (GRDC, http://www.bafg.de) and the European Water Archive (EWA, http://www.bafg.de) compile time series of river discharge all over the world for the GRDC dataset and only for European rivers for the EWA dataset. The time series are updated regularly. There are data series for each country of the Mediterranean basin except Bosnia and Herzegovina, Lebanon, Libya and Malta. However, the count of updated data series decline since the 1990s. The data series of water discharge often do not extend during the 2000s except for France, Slovenia and Cyprus. We haven't data since 1990 for Albania, Croatia, Morocco, Tunisia and Turkey.
2.3 National and regional datasets

2.3.1 Nutrient concentrations


2.3.2 Water discharge

Figure 2. Mediterranean drainage basin, river basins, delineation and elevation at 5 arc-minutes resolution. Delineations and elevation were computed from upscaled 15 arc-seconds HydroSHEDS grids, CCM River and Catchment Database and scientific references.
Chapter 3 - River water discharge

3.1 Delineation of Mediterranean River basins

For most rivers, basin boundaries can be evaluated from digital elevation models. HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) is a mapping product that provides hydrographic information for regional and global-scale applications. It offers a suite of geo-referenced data sets including river basins boundaries, drainage directions, and flow accumulations (Lehner, Liermann & Revenga 2011). HydroSHEDS is based on high-resolution elevation data obtained during a Space Shuttle flight for NASA’s Shuttle Radar Topography Mission (SRTM). In our work, we used the basins boundaries and corrected digital elevation model layers in a 15 arc-second resolution, which is equivalent to a 0.15 km² cell area for mid-latitude. We adjusted the basins boundaries and hydrographic network through comparison with other sources, especially in karst and/ or particularly flat areas. For this, we used CCM River and Catchment Database (Vogt 2007) and the European Water Archive for Europe, and scientific references for the whole Mediterranean drainage basin (Bonacci 1999; Bonacci, Jukić & Ljubenkov 2006; Bonacci & Andric 2008). As most data on other drainage basin characteristics are not available at such accurate resolution, we upscaled these basins boundaries at a 5 by 5 minutes resolution. Boundaries are used to constrain the drainage routing grid. These boundaries are the reference delineations for all data extractions out of the data layers considered in this study. The whole Mediterranean drainage area is almost 4.7 \times 10^6 km² (Figure 2). In previous studies, this area range from 3.5 \times 10^6 km² (Strobl et al. 2009) and 5.6 \times 10^6 km² (Ludwig et al. 2009). This large range is partly due differences in the spatial resolution of digital elevation models and basin delineations in desert regions of the Nile and Northeastern Africa. As no significant runoff or nutrient emissions occur in these desert areas, this uncertainty does not have a major effect on nutrient and water budgeting. The Nile (Table 4), the largest African River, covers roughly 3.0 \times 10^6 km², which is one-tenth the area of Africa and 63% of the whole Mediterranean drainage basin. Surrounded by numerous mountain chains (e.g. Atlas, Apennine, Alps, Dinarids, Hellenids, Taurus Mountains), the other Mediterranean River basins are confined to a relative small coastal fringe with steep terrains (Figure 2). This can be seen Figure 3 when ranking the Mediterranean rivers according to basin size, showing that about half of the Mediterranean drainage basin is formed by river basins smaller than 15 000 km² (not counting the Nile river).
Table 4 Ten largest river basins flowing to the Mediterranean Sea and countries covered by them (bold: countries of the river mouth)

<table>
<thead>
<tr>
<th>River name</th>
<th>Drainage (10^6 km²)</th>
<th>Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nile</td>
<td>2.988</td>
<td>Egypt, Ethiopia, Sudan, South Sudan, Rwanda, Tanzania, Uganda, Burundi,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D.R..Congo, Eritrea, Kenya</td>
</tr>
<tr>
<td>Rhone</td>
<td>0.098</td>
<td>France, Swiss</td>
</tr>
<tr>
<td>Ebro</td>
<td>0.086</td>
<td>Spain</td>
</tr>
<tr>
<td>Po</td>
<td>0.074</td>
<td>Italia</td>
</tr>
<tr>
<td>Moulouya</td>
<td>0.055</td>
<td>Morocco</td>
</tr>
<tr>
<td>Meric (Evros)</td>
<td>0.053</td>
<td>Greece, Turkey, Bulgaria</td>
</tr>
<tr>
<td>Chelif</td>
<td>0.045</td>
<td>Algeria</td>
</tr>
<tr>
<td>Büyük Menderes</td>
<td>0.026</td>
<td>Turkey</td>
</tr>
<tr>
<td>Axios (Vardar)</td>
<td>0.025</td>
<td>Greece, Macedonia</td>
</tr>
<tr>
<td>Orontes (Asi)</td>
<td>0.024</td>
<td>Turkey, Lebanon, Syria</td>
</tr>
</tbody>
</table>

Figure 3 Cumulative distribution of drainage area for Mediterranean River basins (not counting the Nile River)
Figure 4 Interannual average of annual river runoff computed with discharge data series from GRDC, EWA, national and regional databases and completed with interannual values from scientific references.
3.2 Spatial variation of river water discharge

Interannual river water discharge and runoff (i.e. water discharge per unit area) is compiled by river in the Annexes.

Annexe 1. On average, the rivers for which we found discharge series cover about 85% of the Mediterranean drainage basin and 60% excluding the Nile (Figure 4). Most of lacking data are located in North Africa where runoff is assumed to be closed to zero. Basins, where runoff data are available, catch 90% of total precipitation over the Mediterranean drainage basin (71% excluding the Nile). Using the Pike formulation to estimate lacking data (see 3.3.1), we may estimate that our data cover 83% of the total water discharge (with or without the Nile). Largest freshwater discharge is provided by the Rhone with 52.4 km$^3$ yr$^{-1}$ in the Northwestern Mediterranean Sea. The second largest freshwater discharge is provided by the Po to the Adriatic Sea (45.3 km$^3$ yr$^{-1}$). Both rivers of the Northern Mediterranean Sea provide about 25% of the total continental freshwater discharge. Two other rivers discharge more than 10 km$^3$ yr$^{-1}$: Buna-Drini (21.4 km$^3$ yr$^{-1}$) and Nile (about 15 km$^3$ yr$^{-1}$). Among the fourteen rivers discharging more than 5 km$^3$ yr$^{-1}$, six have their mouth along the Adriatic Sea (Po, Buna-Drini, Adige, Soca, Neretva and Vjosa). Others rivers discharging more than 5 km$^3$ yr$^{-1}$ are in Spain (Ebro), Italy (Tevere) and Turkey (Seyhan, Ceyhan, Meric (mouth on the Greece/Turkey boundary) and Susurluk). The size of the drainage basin is the first factor of the spatial variability in freshwater discharge (Figure 5). Thus, the flow of the Nile, the Rhone, the Po, and Ebro are among the highest. Despite this constraint, we observe a strong heterogeneity of freshwater discharge between rivers irrespective of the drainage area. For example, the Nile freshwater discharge is lower than that of Buna-Drini while its drainage area is more than 100 times larger. Expressed per unit area, the river runoff roughly decreases from Northern to Southern Mediterranean Sea. Highest runoffs are gauged in karstic area of the Taurus region (Kopru, Manavgat) and the Eastern Adriatic Sea (more than 1000 mm yr$^{-1}$ for Buna-Drini, Neretva, Soca, Trebisnjica, Mati and Arachtos). For the Manavgat, the calculated runoff reaches more than 3000 mm yr$^{-1}$. This strong discharge (higher than precipitation depth on the topographical drainage area) is probably due to external input of groundwater from farther north endorheic areas. For most African and Southern Spanish rivers, runoff is lower than 25 mm yr$^{-1}$. The Nile, Moulouya and Chelif, runoff are 5, 8 and 13 mm yr$^{-1}$. For the Po and Rhone, it reaches 646 and 548 mm yr$^{-1}$. 
Figure 5 Freshwater discharge and drainage area of Mediterranean rivers
Figure 6: Interannual average of annual precipitation within Mediterranean river basins (1901-2009) calculated from CRU 3.10.1 downscaled at a 5 arc-minutes resolution.
3.3 Main drivers of spatial change in riverine runoff

3.3.1 Climate

A major peculiarity of Mediterranean rivers is related to climatic constraints. Probably the most important criterion in defining the Mediterranean climate type (Peel, Finlayson & McMahon 2007) is related to the strong seasonal rainfall contrast between the summer and winter (autumn) seasons. However, spatial coverage of Mediterranean drainage area is not the same that Mediterranean climate and the drainage basin includes some important variations. The Mediterranean climate covers the drainage basins of Southern Italy, Southern Greece, Middle East and Maghreb. In Spain, climate is dryer and is classified as arid. From the Northern Spain to Northern Adriatic Sea, there are no dry seasons and temperatures are colder. The peculiarity of the Nile is the Northern to Southern climatic gradient with an equatorial climate upstream and desert climate at his middle course and near the mouth.

Using 1901-2009 data from CRU 3.10.1 (Mitchell & Jones 2005), total precipitation and potential evapotranspiration volumes over the Mediterranean drainage basin are 3.0 $10^3$ km$^3$ yr$^{-1}$ and 7.0 $10^3$ km$^3$ yr$^{-1}$. Average precipitation (Figure 6) and potential evapotranspiration depth were 630 mm yr$^{-1}$ and 1487 mm yr$^{-2}$. Precipitation depth ranges from less than 49 mm yr$^{-1}$ to more than 1639 mm yr$^{-1}$. Largest precipitation depths were recorded at the Northern and Eastern Adriatic Sea and in the Rhone basin. Lowest precipitation depths were recorded at the Southern and Southeastern Mediterranean Sea (excluding the Nile). For the five largest basins, the average precipitation depths are 650, 1049, 615, 1233 and 353 mm yr$^{-1}$. Potential evapotranspiration depth ranges from 485 to 1867 mm yr$^{-1}$. Largest potential evapotranspiration depth were calculated were precipitation is lowest and in the Nile basin. Lowest potential evapotranspiration depths were calculated for the Northern Adriatic Sea and for the Rhone. For the five largest basins, the average potential evapotranspiration depth is 1702, 798, 1027, 705 and 1419 mm yr$^{-2}$.

While difference in drainage area explains a large part of the spatial variation in freshwater discharge, precipitation and temperature are the main drivers of spatial variation in runoff, i.e. freshwater discharge per unit of drainage area. Precipitations generate runoff from soils to rivers and temperature influence the potential evapotranspiration from soil to atmosphere. According to Ludwig et al. (2009), quantification of the combined effect of precipitation (P) and temperature on Mediterranean river runoff ($R_0$) can be estimated by the approach of Pike (1964).
Figure 7 Interannual average of average temperature within Mediterranean river basins (1901-2009) calculated from CRU 3.10.1 downscaled at a 5 arc-minutes resolution
\[ R_0 = P \cdot \left(1 - \frac{1}{1 + \left(\frac{P}{58.93 \cdot ABT}\right)^{0.5}}\right) \]

ABT is the annual mean of monthly temperature with negative values set to 0.

The Pike formulation allows a good estimation for major rivers (Nile, Ebro, Rhone, and Po). However, we observe a widespread underestimation for the rivers of the Eastern Ionian and Adriatic Seas and the Southern Italy and Turkey. This underestimation may be due to an underestimation of precipitation or to an overestimation of evapotranspiration. In contrast, the modeled flow is greater than the measured flow for most South Mediterranean Rivers and Spanish Rivers. This overestimation can be partly explained by the impact of water withdrawals, including irrigation, on the observed discharge which is not taken into account in this formulation.
Figure 8 Runoff as function of precipitation (up), and Pike runoff (down). Size of the dots is proportional to the drainage area of each basin.
Figure 9: Agricultural irrigated area for each Mediterranean river basin computed from Harmonized World Soil Database
3.3.2 Water use

Large amounts of water are needed for agriculture, cities and industry. Especially the agricultural productivity of Mediterranean countries is largely dependent on water availability for crops. Irrigation existed for millennia in these regions and has been widely developed over the past decades with cultivated areas expansion and intensification. In Spain, 70% of fresh-water demand is devoted to irrigation (Lorite, Mateos & Fereres 2004). Irrigation is responsible for the highest water consumption due to an increased evapotranspiration rate unlike most of drinking water and industrial water returned to rivers. About 99% of water used in agriculture is lost by crops as evapotranspiration (Rana & Katerji 2000). The “Land Use and Land Cover” grid of the Harmonized World Soil Database map the irrigated and rainfed field at the world scale (Fischer et al 2008). We used these grids to compute irrigated area for each Mediterranean basin. The large basins with largest irrigation rate (Figure 9) are Acheloos (29%), Pinios (24%), Po (22%), Orontes (15%) and Ceyhan (14%). For the Ebro, Rhone and Nile, irrigated areas cover 9%, 4% and 2% of the basin area. Despite a low value for the Nile, irrigated area cover most of the Nile delta. Under the assumption that actual evapotranspiration in irrigated crops is equivalent to the potential evapotranspiration, we can estimate the total evapotranspiration taking into account irrigation effect using this next formulation:

\[ R = R_0 - \frac{A_{irri}}{A} (ETP - E_0) \]

For the Nile and other Northeastern African basins (Figure 10), the water requirement within irrigated area is stronger than the natural runoff. In Northwestern Africa, this water requirements range from 30 to 100% in Morocco and Eastern Algeria and reach 100% of the natural runoff in Tunisia. For the Orontes, this water accounts for 79% of its natural runoff. Despite a very large irrigated area and as the water deficit is relatively low in the Po basin, the impact of irrigation on the water discharge is relatively low compared to the Southern Mediterranean basins where the irrigated area is lower but the water deficit much stronger. For the Nile, the flux of evaporated water within the delta, since the Aswan Dam construction in 1965, is about 20 km³ yr⁻¹, i.e. about 60% of the natural runoff at the delta head (Mikhailova 2001).
Figure 10 Water deficit on irrigated area divided by natural runoff computed from Harmonized World Soil Database and the Pike runoff formulation
Past evolution of river runoff (1960-2009)

Figure 11 Relative runoff change for Mediterranean rivers between 1960 and 2009 and significance threshold of trends (p). Only data series without gap and longer than 20 years was used to compute trend
3.4 Past evolution of freshwater discharge

We performed trend analyses for water discharge data series using the Yue and Pilon method (Yue et al. 2002). The trend slope is estimated with the Theil-Sen approach, if almost equal to zero, then it’s not necessary to conduct the trend analysis. If it differs from zero, then it is assumed to be linear and the data is detrended by the slope and the autoregressive model of order 1 is computed for the detrended series. This is referred to as the Trend Free Pre-whitening procedure. The Mann-Kendall test is applied to the blended series to assess the significance of the trend. Only data series without gap and longer than 20 years was used to compute trend.

Most of the Mediterranean rivers in our compilation of discharge series reveal a strong negative trend (Figure 11). In Maghreb, a significant decrease is observed for the Moulouya (Morocco, -82%) and Medjerda (Algeria, -39%). For the Nile, upstream of Egypt boundary, a 30% decrease was detected between 1960 and 1995. The strongest decrease is observed in the Segura with more than -99% from 1960 to 2009. For the Turia, this decrease reaches 86%. For all Spanish rivers, the decrease is more than 50%. In Greece, significant decreases are calculated for the Nestos, Meric, Strymon and Acheloos and ranged from 65% for Nestos between 1966 and 1995 and 29% for Strymon between 1968 and 1999. For the other Greek rivers, a non-significant but negative slope is computed (Axios and Aliakmon). In Southern Italy, significant runoff decreases are observed for the Ofanto (-63% from 1960 to 1996) and Tevere (-45% from 1960 to 2008). In the Eastern Adriatic Sea, negative trend was detected for the Soca (Slovenia, -29% from 1960 to 1998), Krka (Croatia, -26% from 1960 to 1998), Shkumbini (Albania, -41% from 1960 to 1990) and Osumi (Albania, -38% from 1960 to 1989). For Northern Italy (Adige, Po, Arno) and the Rhone river, no significant trend was detected in the time series. The only positive value, but non-significant, was computed for the Imera Mediridionale in Sicilia. In Annex 1, river runoff for the last 20 years recorded is lower than value over whole time series for 88% of rivers. Expressed in water depth (Figure 12), the highest significant decreases are computed for the Acheloos (-20 mm yr⁻¹), Shkumbini (-15 mm yr⁻¹), Nestos (-9mm yr⁻¹) and Krka (-6 mm yr⁻¹). For the Segura, Turia and Moulouya, where the relative decrease is maximal, the absolute decrease is lower than 2 mm yr⁻¹. This general runoff decrease for Mediterranean rivers was also shown for the whole twentieth century (Milly, Dunne & Vecchia 2005).
Figure 12 Absolute runoff change for Mediterranean rivers between 1960 and 2009 and significance threshold of trends (p). Only data series without gap and longer than 20 years was used to compute trend.
Figure 13 Absolute precipitation change for Mediterranean rivers between 1960 and 2009 computed from downscaled CRU 3.10.1 data and significance threshold of trends (p)
3.5 Main drivers of freshwater discharge evolution

3.5.1 Climate

As for spatial variability, interannual change in freshwater discharge is mainly controlled by precipitation change. Precipitation is highly variable from year to year but long-term trends can be observed. Philandras et al. (2011) showed that statistically significant negative trends of the annual precipitation totals exist in the majority of Mediterranean regions during the period 1901–2009, with an exception of northern Africa, southern Italy where slight positive trends (not statistically significant) appear. For the 1960-2009 period, only one significant trend (Ebro) was calculated among the twenty largest Mediterranean basins (Figure 13). However, the slope, non significant, is negative for most of the Mediterranean Rivers except Middle Northern Africa and Southern Italy. Significant decreasing trends are computed for many rivers of the Eastern Adriatic and Ionian Seas, central Italy, Northern Spain and Eastern Levantine Sea.

For Ebro, rainfall decreased by 104 mm in the last 50 years (15% of the interannual average centered on 1960). Decreases greater than 300 mm are calculated for the Serchio and Reno in Italy. By comparing the slope of changes in precipitation and flow rates (Figure 14), we note that for most runoff decreases, we also observe a decrease in precipitation.

Figure 14 Runoff and precipitation trend between 1960 and 2009 in Mediterranean Rivers. Blue dot: significant trend for precipitation, green dot: significant trend for runoff, red dot: significant trend for both precipitation and runoff, grey dot: non-significant trends. Only water discharge data series without gap and longer than 20 years was used to compute trend.
Figure 16 Actual annual river runoff (hatched: modeled runoff calculated with climatic data of IMAGE 2.4 for 2000s, non-hatched: gauged runoff (Figure 4))
3.6 Budget and future scenarios for riverine runoff

To assess the actual water discharge by rivers in the Mediterranean Sea, we used the past 20 years average of annual data series or interannual average when data series are not available. For other rivers, we used the Pike formulation (Figure 16). Actual water discharge by rivers is about 402 km$^3$ yr$^{-1}$. This estimation is closed to the previous assessment of Margat & Treyer (2004), with 396 km$^3$ yr$^{-1}$ (not accounting for groundwater discharge). Other values from recent studies are lower and range from 320 (excluding the Nile) to 350 km$^3$ yr$^{-1}$ (Boukhir & Barnier 2000s; Ludwig et al. 2009; Boudouch, Girrezetti & Aloe 2010). Freshwater discharge to the Adriatic Sea reaches 155 km$^3$ yr$^{-1}$, i.e. 38.5% of total freshwater discharge (Table 5). The Northwestern Mediterranean Sea, Aegean Sea and Northern Levantine Sea receive 85, 50 and 45 km$^3$ yr$^{-1}$. Sum of freshwater provided by the Northern Mediterranean Rivers covers 93% of the total freshwater discharge. With about 15 km$^3$ yr$^{-1}$, the Nile discharges 59% of the total freshwater provided by Southern Mediterranean Rivers.

Climatic scenarios used to assess freshwater discharge in 2030s were provided by the IMAGE 2.4 model of the Netherland Environmental Assessment Agency (MNP, 2006). One of the peculiarities of the IMAGE model is that the future climate is directly linked to the socioeconomic development via the release of greenhouse gases to the atmosphere. This implies that climatic scenarios associated with the four socioeconomic scenarios (see 4.6.1) are not the same. For 2030s, we calculate a decrease of 11.6 to 12.0% depending on the scenario used, i.e. a total freshwater discharge between 354 and 360 km$^3$ yr$^{-1}$. Other studies show that this decrease is expected to continue during the next decades (Mariotti et al. 2008; Elguindi et al. 2009). However, these scenarios do not take account of irrigation and reservoir capacity change in the next decades. Due to the demographic growth and intensification of agriculture projected for the Eastern and Southern Mediterranean basins, the decline of water discharge should be stronger than these calculated values.

Table 5 Average actual freshwater fluxes (km$^3$ yr$^{-1}$) to the Mediterranean Sea and 2030s scenarios

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Figure 17 (A) Box plot of concentrations in Mediterranean rivers for phosphorus and nitrogen compounds and (B) concentrations in dissolved inorganic nitrogen as function of nitrate concentrations (up) and total phosphorus as function of dissolved inorganic phosphorus concentrations (down).
Chapter 4 - Nutrient concentrations and fluxes

4.1 Forms and concentrations of nitrogen and phosphorus in rivers

Various organic and inorganic compounds have to be taken into account nitrogen and phosphorus fluxes by rivers. Inorganic nitrogen compounds include nitrate (NO$_3$), ammonia (NH$_4$) and nitrite (NO$_2$). Wastewaters are the main source for NH$_4$ and NO$_2$. In agricultural area, fertilizer and manure excess is the main source for NO$_3$. Other sources of NO$_3$ are biological fixation and atmospheric deposition. Nitrite concentrations are, in most of case, very low beside other inorganic compounds and may be omitted in the nitrogen budget. From collected data at the basin scale and weighting the nutrient concentration of each basin by their water discharge, the average NO$_3$, NH$_4$ and NO$_2$ concentrations were 1.91 mgN L$^{-1}$, 0.21 mgN L$^{-1}$ and 0.05 mgN L$^{-1}$, i.e. an average dissolved inorganic nitrogen (DIN) concentration of 2.17 mgN L$^{-1}$ (Figure 17). For dissolved organic nitrogen (DON), the average concentration is 0.92 mgN L$^{-1}$, i.e. 25% of total dissolved nitrogen (TDN) concentration. Lacking data for other nitrogen compounds than NO$_3$, we may estimate the DIN and TDN concentrations from NO$_3$ concentration. Indeed, in most cases, NO$_3$ is the dominant nitrogen form and his concentration covaries in space with other nitrogen compounds. In some rivers, concentrations of NH$_4$ and DON may be unusually strong compared to NO$_3$. This indicates strong wastewater emission closed to the river mouth and a relatively low water discharge. TDN or DIN concentrations may be estimated from NO$_3$ concentration using the following equations:

\[ C_{DIN} = 1.16 \cdot C_{NO3} \quad (R^2=0.91, \text{n}=102) \]

\[ C_{TDN} = 1.32 \cdot C_{NO3} + 0.13 \quad (R^2=0.79, \text{n}=51) \]

Particulate phosphorus (PP) accounts for a high fraction of phosphorus fluxes in rivers because of strong affinity between orthophosphate (majority dissolved from, PO$_4$) and particulates. At a global scale, dissolved phosphorus only constitutes about 10% of the phosphorus fluxes by rivers (Meybeck 1982). For Mediterranean Rivers, average dissolved inorganic phosphorus (DIP) concentration is 0.16 mgP L$^{-1}$ and 0.10 mgP L$^{-1}$ when concentrations are weighted by water discharge. There are numerous data for total phosphorus (TP). However, the number of measurement and sampling strategy are not suitable for evaluating concentrations or fluxes on an annual basis. In many cases, TP concentrations are measured out of flood periods while TP concentrations are much stronger during floods. From collected data, average TP concentration is 0.21 mgP L$^{-1}$ and 0.10 mgP L$^{-1}$ when concentrations are weighted by water discharge. In fact, average concentrations should be greater and it is likely that the average concentrations of TP measured out during floods are rather representative for total dissolved phosphorus (TDP) concentrations (i.e. dissolved inorganic and organic phosphorus). We note a strong relation between TP and DIP concentrations:

\[ C_{TDP} = 1.21 \cdot C_{DIP} + 0.06 \quad (R^2=0.82, \text{n}=87) \]
Figure 18 Interannual average of nitrate concentrations in Mediterranean rivers calculated from available 2000-2010 data or most recent interannual value from scientific references.
4.2 Spatial variation of nutrient concentrations and fluxes

4.2.1 Nitrogen

4.2.1.1 Nitrogen concentration

Lowest \( \text{NO}_3 \) concentrations (Figure 18) were found in rivers of the Eastern Adriatic Sea with most values lower than 0.5 mgN L\(^{-1} \) and minimum values lower than 0.2 mgN L\(^{-1} \) at the river mouth of Trebisnjica (Bosnia and Herzegovina), Mati (Albania) and Licka (Croatia). Fairly low values were also observed at the Eastern Ionian Sea and Southern Turkey (excluding Orontes). In contrast, Orontes has the strongest concentration of \( \text{NO}_3 \) with 12.7 mgN L\(^{-1} \). Strong \( \text{NO}_3 \) concentrations were also recorded in Spanish rivers, especially in the Southern basins, and in the Maghreb. Values were often greater than 4 mgN L\(^{-1} \) (Segura, Jucar, Turia, Vinalopo, Tafna, Mazafran and Chelif). In Italia, values greater than 3 mgN L\(^{-1} \) were found in southern small coastal basins (Fortore, Metauro, Sinni, Marta, Trigno), in Sicilia (Simeto, Imera) and Sardinia (Flummini Mannu, Cedrino). For the Rhone, Ebro and Po, average \( \text{NO}_3 \) concentrations were respectively 1.5, 2.5 and 2.4 mgN L\(^{-1} \). Most of the Nile freshwater (15 km\(^3 \), Nixon 2003) is discharged to the sea by the drainage network flowing to the coastal lagoons (13.6 km\(^3 \), Oczkowski et al. 2008)). The average TDN concentration in drainage water is 14.5 mgN L\(^{-1} \) (Khalil, Ouarda & St-Hilaire 2011) with values ranged from 6.8 to 25.3 mgN L\(^{-1} \). Average \( \text{NO}_3 \) concentration in drainage water is between 4.9 to 10.9 mgN L\(^{-1} \) for six categories of drainage water closed to the coastal line (Shaban et al. 2010). Weighting these \( \text{NO}_3 \) concentrations by the respective area covered by these six categories, the average \( \text{NO}_3 \) concentration in drainage water is 7 mgN L\(^{-1} \). We could deduce an average concentration of Kjeldahl nitrogen (NH\(_4\) and DON) of 7.5 mgN L\(^{-1} \).

For NH\(_4\) (Figure 19), lowest concentrations were also found in the Eastern Adriatic Sea with less than 0.02 mgN L\(^{-1} \) in all Croatian rivers (Cetina, Licka, Mirna, Gacka and Krka). Values lower than 0.10 mgN L\(^{-1} \) were recorded at the Northern Adriatic Sea, in France, Spain and, more locally, in Western Greece, Southern Italia and Turkey. Greatest NH\(_4\) concentrations were measured in small basins including a large city closed to the river mouth: 11.6 mgN L\(^{-1} \) in Besos closed to Barcelona and 5.9 mgN L\(^{-1} \) in Regi Laghi closed to Naples. Concentrations greater than 0.5 mgN L\(^{-1} \) were found in most Maghreb rivers, around the Aegean Sea (including the largest basin, Merci), at the Southern Italia (including the two largest basins: Tevere and Arno) and in Spain (as Segura). For the Rhone, Ebro and Po, NH\(_4\) concentrations were 0.07, 0.07 and 0.09 mgN L\(^{-1} \). We have no measured values for the Nile.
Figure 19 Average ammonium concentrations in Mediterranean rivers calculated from available 2000-2010 data or most recent interannual value from scientific references.
Figure 20 Average nitrite concentrations in Mediterranean rivers calculated from available 2000-2010 data or most recent interannual value from scientific references
Regarding DON (Figure 21), data coverage is limited to Western Mediterranean Sea. As other nitrogen forms, lowest values were observed at the Eastern Adriatic Sea with less than 0.25 mgN L⁻¹. Strongest values were recorded, as NH₄, in Besos and Regi Lagni with, respectively, 5.3 and 7.5 mgN L⁻¹. In Southern Spain, concentrations higher than 1 mgN L⁻¹ were recorded in Guadalhorce, Almanzora and Vinalopo. In Northern Italia, Arno and Po have strong DON content with 1.9 and 2.0 mgN L⁻¹. In Ebro and Rhone, organic nitrogen concentrations were 0.47 and 0.35 mgN L⁻¹.
Figure 21 Average dissolved organic nitrogen concentrations in Mediterranean rivers calculated from available 2000-2010 data or most recent interannual value from scientific references
Figure 22 Average nitrate flux by Mediterranean Rivers calculated from available 2000-2010 data for nutrient concentrations and average water discharge on the last 20 years or most recent interannual value for nutrient and water discharge from scientific references.
4.2.1.2 Nitrogen fluxes

Strongest river fluxes of NO$_3$ (Figure 22) are provided by the four largest basins with $106 \ 10^3$, $105 \ 10^3$, $78 \ 10^3$ and $21 \ 10^3$ tN yr$^{-1}$ for the Nile, Po, Rhone and Ebro. Expressed as specific fluxes, among the thirteen basins with a flux stronger than 1000 kgN km$^{-2}$ yr$^{-1}$, twelve are Italian basins. More than 3000 kgN km$^{-2}$ yr$^{-1}$ is found for the rivers Soca and Livenza (Northern Adriatic Sea). Excluding some small coastal basins, fluxes are always greater than 500 kgN km$^{-2}$ yr$^{-1}$ in Italian rivers. NO$_3$ flux of the Rhone is also elevated with 820 kgN km$^{-2}$ yr$^{-1}$. Other fluxes greater than 500 kgN km$^{-2}$ yr$^{-1}$ are found in rivers of the Eastern Adriatic and Ionian Seas (Thyamis, Alfeios, Sperchios, Erzeni, Mirna) and of the Southwestern Turkey (Seyhan, Ceyhan, Orontes). Lowest fluxes are measured on the South Mediterranean Rivers, Southern Spain, South and Western Turkey with, for most rivers, less than 100 kgN km$^{-2}$ yr$^{-1}$.

For NH$_4$ (Figure 23), greatest fluxes are not provided by largest basins. Greatest NH$_4$ flux is provided by Drini (Southern Adriatic Sea) with $8.1 \ 10^3$ tN yr$^{-1}$. Then, respectively, the next important fluxes are $4.8 \ 10^3$, $4.1 \ 10^3$, $4.0 \ 10^3$ and $3.9 \ 10^3$ tN yr$^{-1}$ for Küçük Menderes, Po, Tevere and Meric. In Rhone and Ebro, NH$_4$ fluxes are $3.7 \ 10^3$ and $0.6 \ 10^3$ tN yr$^{-1}$. Per unit area, fluxes higher than 200 kgN km$^{-2}$ yr$^{-1}$ were found in Italia (Tevere, Arno, Sele, Magra, Crati, Fortore and Serchio). Other values higher than 200 kgN km$^{-2}$ yr$^{-1}$ were found in Têt (France), West Kebir (Algeria), and Küçük Menderes (Turkey). Greatest NH$_4$ flux is observed in the Besos with more than 1500 kgN km$^{-2}$ yr$^{-1}$. Around the Aegean Sea, flux is higher than 100 kgN km$^{-2}$ yr$^{-1}$ in Pinios, Acheloos (Greece) and Gediz (Turkey). In Southeastern Turkey, NH$_4$ fluxes are about 100 kgN km$^{-2}$ yr$^{-1}$ (Seyhan, Ceyhan, Berdan). Lowest fluxes were calculated for Western Maghreb and Spain with, for most rivers, less than 10 kgN km$^{-2}$ yr$^{-1}$.

Five rivers discharge more than $1.0 \ 10^3$ tN yr$^{-1}$ of NO$_2$ (Figure 24): Rhone, Po, Meric, Seyhan and Tevere. Per unit area, maximum values were calculated at the Eastern Ionian Sea with more than 100 kgN km$^{-2}$ yr$^{-1}$ in Thyamis, Alfeios (Greece) and Shkumbini (Albania). fluxes for most other rivers of the Eastern Ionian Sea were stronger than 20 kgN km$^{-2}$ yr$^{-2}$. In the Besos, flux is also stronger than 100 kgN km$^{-2}$ yr$^{-1}$. Values stronger than 20 kgN km$^{-2}$ yr$^{-1}$ were found for numerous Italian rivers (Tevere, Bacchiglione, Volturino, Sele, Ofanto, Livenza, Magra, Serchio, Sangro, Tronto, Trigno). For Seyhan and Ceyhan (Southeastern Turkey), NO$_2$ flux is also strong. Around the Aegean Sea, values range between 10 and 20 kgN km$^{-2}$ yr$^{-1}$. Minimal values are found in the Northeastern Adriatic Sea, Spain, Maghreb and Southern Turkey with less than 5 kgN km$^{-2}$ yr$^{-1}$ for most rivers. Fluxes for Po, Rhone, Ebro and Meric are 19, 11, 3 and 20 kgN km$^{-2}$ yr$^{-1}$. 

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Figure 23 Average ammonium flux by Mediterranean Rivers calculated from available 2000-2010 data for nutrient concentrations and average water discharge on the last 20 years or most recent interannual value for nutrient and water discharge from scientific references.
Figure 24 Average nitrite flux by Mediterranean Rivers calculated from available 2000-2010 data for nutrient concentrations and average water discharge on the last 20 years or most recent interannual value for nutrient and water discharge from scientific references.
Figure 25 Average dissolved organic nitrogen flux by Mediterranean Rivers calculated from available 2000-2010 data for nutrient concentrations and average water discharge on the last 20 years or most recent interannual value for nutrient and water discharge from scientific references.
For DON (Figure 25), fluxes of Rhône, Po and Ebro are $24.6 \times 10^3$, $90.1 \times 10^3$ and $3.0 \times 10^3$ tN yr$^{-1}$. Strongest fluxes per unit area are calculated in the Northern Adriatic Sea with 1268 kgN km$^{-2}$ yr$^{-1}$ in Po and 1202 kgN km$^{-2}$ yr$^{-1}$ in Livenza. In Spain, excluding Besos where flux reaches 258 kgN km$^{-2}$ yr$^{-1}$, values are lower than 100 kgN km$^{-2}$ yr$^{-1}$. 
Figure 26 Average dissolved inorganic phosphorus concentrations in Mediterranean rivers calculated from available 2000-2010 data or most recent interannual value from scientific references.
4.2.2 Phosphorus

4.2.2.1 Phosphorus concentrations

**DIP** concentrations range from 0.01 mgP L\(^{-1}\) to 1.40 mgP L\(^{-1}\) (*Figure 26*). Minima were found in the rivers of the Eastern Adriatic and Aegean Seas with less than 0.05 mgP L\(^{-1}\) pour for most rivers. In France, concentrations are also low with in average 0.05 mgP L\(^{-1}\). Around the Aegean Sea, concentrations are often stronger than 0.20 mgP L\(^{-1}\) and reach 0.54 mgP L\(^{-1}\) for Axios, 0.48 mgP L\(^{-1}\) for Meric, 0.34 mgP L\(^{-1}\) for Gediz and 1.34 mgP L\(^{-1}\) for Kütük Menderes. Strong concentrations were measured in Maghreb with 0.80 mgP L\(^{-1}\) in Moulouya and 0.49 mgP L\(^{-1}\) in Kebir-Rhumel. Some other levels greater than 0.30 mgP L\(^{-1}\) were found in Ası (Turkey), Besos (Spain), Llobregat (Spain), Regi Lagni and Serchio (Italy). In Rhone, Po and Ebro, concentrations are 0.05, 0.07 and 0.06 mgP L\(^{-1}\).

For **TP** (*Figure 27*), concentrations range from less than 0.01 mgP L\(^{-1}\) and 1.89 mgP L\(^{-1}\). Most of concentrations stronger than 0.40 mgP L\(^{-1}\) are around Aegean Sea (Meric, Axios, Gediz, Strymon, Aliakmon, Kütük Menderes, Loudias and Bakır). Other rivers with so strong concentrations are Besos (maximum concentration), Llobregat and Guadalhorce in Spain, Regi Lagni and Ofanto in Italy, and Seyhan in Turkey. In Italia, TP concentrations are often stronger than 0.10 mgP L\(^{-1}\) and stronger than 0.20 mgP L\(^{-1}\) for Po, Tevere and Arno. In Northern Spain and France, concentrations are lower than 0.10 mgP L\(^{-1}\) for most rivers, with 0.07 mgP L\(^{-1}\) for Ebro and 0.08 mgP L\(^{-1}\) for Rhône.
Figure 27 Average total phosphorus concentrations in Mediterranean rivers calculated from available 2000-2010 data or most recent interannual value from scientific references
Figure 28 Average dissolved inorganic phosphorus flux by Mediterranean Rivers calculated from available 2000-2010 data for nutrient concentrations and average water discharge on the last 20 years or most recent interannual value for nutrient and water discharge from scientific references.
4.2.2.2 Phosphorus fluxes

The highest DIP flux (Figure 28) is calculated for the Meric and Po with more than $3 \times 10^3$ tP yr$^{-1}$. Four other rivers have a DIP flux stronger than $1 \times 10^3$ tP yr$^{-1}$: the Rhône, Axios, Seyhan and Küçük Menderes. For the Ebro, the flux is only $0.5 \times 10^3$ tP yr$^{-1}$. Per unit area, highest values are observed in Italy, around the Aegean Sea, in the Southeastern Turkey and Northeastern Maghreb. Values are higher than 50 kgP km$^{-2}$ yr$^{-1}$ for the Axios, Meric, Strymon, Pinios and Thyamis in Greece, for the Küçük Menderes and Seyhan in Turkey, for the Arno, Bacchiglione, Serchio, Magra and Marta in Italy, for the West Kebir in Algeria and for the Besos in Spain. In the Rhone, Po and Ebro, flux is respectively 27, 45 and 6 kgP km$^{-2}$ yr$^{-1}$. Minimales values are observed in the Southeastern Spain and Eastern Adriatic Sea with less than 5 kgP km$^{-2}$ yr$^{-1}$.

Strongest TP fluxes are measured in the Po, Meric and Rhone with $9.1 \times 10^3$, 5.1 and 4.2 tP yr$^{-1}$ (Figure 28). Fluxes higher than 1 tP yr$^{-1}$ are observed in the Axios, Aliakmon and Strymon in Greece, the Ceyhan, Seyhan and Küçük Menderes in Turkey, the Buna-Drini in Albania and the Tevere in Italy. Per unit area, we observe the same spatial change than for DIP with value ranged from 1 (Guadalfeo, Spain) to 374 kgP km$^{-2}$ yr$^{-1}$ (Küçük Menderes, Turkey). For the Rhone, Ebro, Po and Meric, this flux is 44, 8, 127 and 96 kgP km$^{-2}$ yr$^{-1}$.
Figure 29 Average total phosphorus flux by Mediterranean Rivers calculated from available 2000-2010 data for nutrient concentrations and average water discharge on the last 20 years or most recent interannual value for nutrient and water discharge from scientific references.
Figure 30 Nitrogen emissions by natural areas in 2000s
4.3 Main drivers of spatial variations in nutrient concentrations and fluxes

4.3.1 Nutrient emissions

4.3.1.1 Data sources

Nutrient balance data was provided by the IMAGE 2.4 model of the Netherland Environmental Assessment Agency (MNP, 2006). Point sources of nutrient were calculated using the conceptual relationship of Van Drecht et al. (2009) between per capita human N and P emission from human excreta and other household and industrial wastes, and per capita income. The amount of phosphorus or nitrogen discharged to surface water is estimated using removal of nutrient in wastewater treatment (expressed as a fraction of nutrient effluent to treatment plants) and the fraction of population connected to sewage systems. Non-point nutrient balance includes nutrient inputs and outputs for a given area of land. Nutrient inputs include application of synthetic fertilizer and animal manure for both phosphorus and nitrogen by crop category. It also includes biological fixation and atmospheric deposition only for nitrogen. Nutrient outputs include crop exportation. This nutrient balance not take into account evolution of nutrient storage and removal within soil and groundwater. These data produced at a 0.5 by 0.5 degrees were downscaled at a 5 by 5 minutes using a simple bilinear interpolation. New data produced in the framework of PERSEUS (http://www.perseus-net.eu/site/content.php) would be produced from IMAGE at 5 by 5 minutes and would allow a better estimation of nutrient balance at this spatial resolution.

4.3.1.2 Nutrient emissions in natural areas

Processes accounting for nitrogen emission in natural area are atmospheric deposition and biological fixation. Atmospheric deposition accounts for different nitrogen sources including energy-related, biomass burning, agricultural and natural emissions of nitrogen oxides and ammonia to air (Bouwman et al., 2002). So, emissions within closed agricultural and urban area have a strong effect on nutrient emissions within natural area. Natural nitrogen emissions (Figure 30) range from <1 to 3060 kgN km\(^{-2}\) yr\(^{-1}\). At the scale of the whole Mediterranean drainage basin, theses emissions reach 4.3 \(10^6\) TN i.e. 35% of the total diffuse emissions. For the five largest river basins of the Mediterranean Sea, natural emissions account for 39, 54, 22, 20 and <1% of total diffuse emissions for, respectively, the Nile, Rhone, Po, Ebro and Moulouya rivers.

For phosphorus, the atmospheric fluxes are negligible with about 0.5 percent of inputs to rivers (Meybeck 1982). Globally, natural weathering account for 24% of the
Figure 31 Nitrogen emissions by agricultural areas in 2000s
dissolved inorganic phosphorus delivered to the ocean (Harrison et al. 2010), i.e. 26 kgP km$^{-2}$ yr$^{-1}$. We have no data to estimate spatial variation of phosphorus emissions by weathering within the Mediterranean area.

4.3.1.3 Nutrient emission in agricultural area

Total nitrogen input in agricultural area reach $14.3 \times 10^6$ tN yr$^{-1}$ and $1.9 \times 10^6$ tP yr$^{-1}$ in the Mediterranean drainage basin. Manure and fertilizer account for $6.9 \times 10^6$ tN yr$^{-1}$ i.e. 76% of the total nitrogen inputs in agricultural area, and, for phosphorus, $0.7 \times 10^6$ tP yr$^{-1}$. Atmospheric deposition and biological fixation of nitrogen are $1.9 \times 10^6$ tN yr$^{-1}$. Deducing crop export, total nitrogen and phosphorus emissions in agricultural area are $12.3 \times 10^6$ tN yr$^{-1}$ i.e. 95% of the total diffuse emission of nitrogen and $0.8 \times 10^6$ tP yr$^{-1}$.

Emissions per unit area range from <1 to 26400 kgN km$^{-2}$ yr$^{-1}$ for nitrogen (Figure 31) and from <1 to 26.5 $10^3$ kgP km$^{-2}$ yr$^{-1}$ for phosphorus (Figure 32). Strongest emissions, for both phosphorus and nitrogen, are observed in Southern Spain, Northern Italia, Western Turkey, Israel, Lebanon and Syria.

For the five largest river basins, respectively the Nile, Rhone, Ebro, Po and Moulouya, nitrogen emission in agricultural area are $2.5 \times 10^3$, $3.5 \times 10^3$, $3.9 \times 10^3$, $5.0 \times 10^3$ and $1.1 \times 10^3$ kgN km$^{-2}$ yr$^{-1}$ and phosphorus emissions are $0.12 \times 10^3$, $0.07 \times 10^3$, $0.48 \times 10^3$, $0.76 \times 10^3$ and $0.06 \times 10^3$ kgN km$^{-2}$ yr$^{-1}$.

Several studies confirm this elevated agricultural emissions and their relation with water quality. In the Valencia region (Spain), nitrogen emissions range from 15000 to 30000 kgN km$^{-2}$ yr$^{-1}$ under vegetables crops (Ramos, Agut & Lidón 2002). In the Almeria region, nitrate concentration in groundwater is atmest 100 mgN L$^{-1}$ under greenhouses (Thompson et al. 2007). More than 20 mgN L$^{-1}$ are measured in groundwater of the Low Almanzora. In Lebanon, the nitrogen emissions is higher in the Litani valley with atmest 78000 kgN km$^{-2}$ yr$^{-1}$ under vegetables crops and nitrate concentration in groundwater higher than 38 mgN L$^{-1}$. In the Po valley, phosphorus emissions in agricultural area reach 11000 kgP km$^{-2}$ yr$^{-1}$ (Torrent, Barberis & Gil-Sotres 2007). High nitrate concentration in rivers is always linked with strong nitrogen emissions due to agricultural practices. However, for nitrate flux, this link is less obvious as nitrate flux is also greatly controled by spatial change in water discharge.
Figure 32 Phosphorus emissions by agricultural areas in 2000s
Figure 33 Nitrogen emissions by wastewaters in 2000s
4.3.1.4 Nutrient emission by wastewaters

Nutrient emission by wastewaters is 0.6 \(10^6\) tN yr\(^{-1}\) and 0.1 \(10^6\) tP yr\(^{-1}\) for the whole Mediterranean drainage basin, i.e. 5% and 6% of total emissions (including diffuse emissions in agricultural and natural areas). Emissions per unit area range from <1 to 11 \(10^3\) kgN km\(^{-2}\) yr\(^{-1}\) for nitrogen and from <1 to 2.4 \(10^3\) kgP km\(^{-2}\) yr\(^{-1}\) for phosphorus. For both phosphorus and nitrogen, strongest emission rates are located in small basin including large cities (Figure 33, Figure 34). Some large basins of Italy, Northern Maghreb and southwestern Turkey have emission rates larger than 0.4 \(10^3\) kgN km\(^{-2}\) yr\(^{-1}\) and 0.1 \(10^3\) kgP km\(^{-2}\) yr\(^{-1}\). For the Nile, Rhone, Ebro, Po and Moulouya basins, nitrogen emission by wastewaters are 0.03, 0.24, 0.10, 0.75 and 0.03 \(10^3\) kgN km\(^{-2}\) yr\(^{-1}\) and phosphorus emission are 0.01, 0.05, 0.02, 0.13 and 0.01 \(10^3\) kgP km\(^{-2}\) yr\(^{-1}\).
Figure 34 Phosphorus emissions by wastewaters in 2000s
Figure 35 Retention fraction of diffuse nitrogen sources
4.3.2 Nutrient leaching, storage and removal

Only a limited fraction of the total anthropogenic inputs of nutrient to watersheds is actually exported by rivers to the coastal zone. This accounts for the net effect of various biogeochemical processes responsible for temporary or permanent removal from the water phase (such as biological uptake and biomass production, sedimentation and denitrification for nitrogen) or removal from the land phase (such as gaseous losses by denitrification and nitrification, volatilization and storage in permanent vegetation, soils and groundwater).

4.3.2.1 Nutrient leaching, storage and removal within soil and subsoil

Main driver of nutrient leaching from soils to rivers are precipitation or runoff. At the global, regional scale or for the Mediterranean drainage area, the spatial variability of the nitrogen retention could be correlated with precipitation or river runoff (Howarth et al. 2006; Billen et al. 2009; Ludwig et al. 2010). The ratio of diffuse source discharged to river as dissolved inorganic form may be estimated using these conceptual formulations (Dumont et al. 2005; Harrison et al. 2010):

\[ C_{\text{DIN,soil/subsoil}} = 0.94 \cdot R \]

\[ C_{\text{DIP,soil/subsoil}} = \frac{0.04}{1 + \left(\frac{R}{0.85}\right)^{-2}} \]

For nitrogen (Figure 35), less than 1% of diffuse source are discharged as dissolved inorganic nitrogen (DIN) to Southern Mediterranean Rivers. In the Northern Mediterranean Rivers, this rate increase with more than 10% for Eastern Adriatic Rivers. For the Nile, Rhone, Ebro, Po and Moulouya rivers, it reach <1%, 54%, 10%, 63% and 1%. For phosphorus (Figure 36), diffuse emission of dissolved inorganic phosphorus (DIP) account for less than 10% of diffuse sources for most basins. For the Nile, Ebro and Moulouya, emission of diffuse source to rivers is less than 1%. For the Rhone and Po rivers, it reaches 9 and 11%. Regardless of the nitrogen and phosphorus diffuse emissions, basins of Eastern Adriatic and Ionian Seas have the highest risk of nitrogen and phosphorus leaching from soil to rivers. Because of the relatively low diffuse emissions of nitrogen and phosphorus in Eastern Adriatic, the flux of diffuse nitrogen and phosphorus from soils to rivers is low relative to other regions previously cited, especially in the Northern Adriatic. This vulnerability is increased for nitrogen as diffuse emissions are the main source of nitrogen discharged to the rivers.
Figure 36 Retention fraction of diffuse phosphorus sources
Figure 37 Water residence time in reservoirs (years)
4.3.2.2 Nutrient storage/removal within reservoir and dams

Lentic water bodies (lakes and reservoirs) have the potential to act as important sources for nitrogen and phosphorus as it is transported across the landscape because they offer ideal conditions for nitrogen or phosphorus burial in sediments or permanent loss of nitrogen via denitrification (Harrison et al. 2008). The Global Reservoir and Dam Database 1.1 (Lehner et al. 2011) compiles reservoirs with a storage capacity of more than 0.1 km³. The recent version contains 429 spatially explicit records of reservoirs for the Mediterranean drainage basin and gives information in their storage volume. Estimation of nutrient storage/removal within reservoirs and dams may be estimated using calibrated conceptual formulation at a global scale (Wilhelmus, Bernhardt & Neuman 1978, Seitzinger et al. 2002):

\[
C_{\text{DIP,res}} = 1 - 0.85 \cdot \left(1 - e^{-0.0807 \cdot 365 \cdot \frac{V_{\text{res}}}{R_0}}\right)
\]

\[
C_{\text{DIN,res}} = 1 - 0.8845 \cdot \left(\frac{Z_{\text{res}}}{\frac{V_{\text{res}}}{R_0}}\right)^{-0.3677}
\]

\[\frac{V_{\text{res}}}{R_0}\] is the average residence time of water in reservoirs (effective reservoir volume divided by average annual discharge, (Figure 37)). \(Z_{\text{res}}\) is the average reservoirs depth. \(C_{\text{DIP,res}}\) and \(C_{\text{DIN,res}}\) are export fractions for dissolved inorganic phosphorus and dissolved inorganic phosphorus.

For nitrogen (Figure 38), the retention fraction reaches almost 100% for the Nile, Segura and Almanzora rivers. Retention higher than 30% is calculated for some large basins of Algeria (Chellif and Macta-Hammam), Tunisia (Medjbera, Joumine, Miliane) and Spain (Guadalhorce and Guadalfeo). In Spain, this retention fraction is higher than 20% for all large basins. Retention fraction is higher than 20% in Morocco (Mouloiy), Southern Italia (Bradano, Fortore, Flumendosa), in Greece (Meric, Acheloos, Alakmon), in Turkey (Orontes). As the only reservoirs with storage capacity higher than 0.1 km³ are listed in the Global Reservoir and Dam Database 1.1, retention fraction for small basins could be much higher than calculated value.

For phosphorus (Figure 39), the calibrated formulation induces a very low spatial variation of retention fraction and for most basins the retention fraction reaches the maximum retention fraction of the formulation (i.e.: 85%). Lowest retention fraction (excluding null value due to no reservoirs or lack of data for small reservoirs) is calculated for Northern Adriatic including the Po with 60%.
Figure 38 Retention fraction of nitrogen by reservoirs
Figure 39 Retention fraction of phosphorus by reservoirs
4.3.2.3 Nutrient storage/removal by water abstraction

Water removed from rivers for human consumption or irrigation and domestic and industrial use may be returned to the river or lost (consumed) permanently, primarily through evapotranspiration on irrigated lands and interbasin transfers. Biogeochemical constituents associated with net, consumptive water use are assumed to be permanently removed from the river system. So, the fraction of river flux remove consumptively ($C_{abs}$) could be estimated from total river discharge at the mouth before ($R_0$) and after ($R$) the implementation of large-scale irrigation and other water withdrawal schemes (Mayorga et al. 2010):

$$C_{abs} = 1 - \frac{R}{R_0}$$

Length of discharge data series are often too short for estimate the natural river discharge before these implementations. Approximation of the natural runoff ($R_0$) may be done using conceptual rainfall/runoff model. Here, we used the Pike formulation (see 3.3.1) to estimate this natural runoff as done in previous studies for the Mediterranean drainage basin (Ludwig et al. 2009, 2010). Greatest water abstractions are calculated for the Nile, the Eastern Maghreb and Southern Spain (Figure 40). Less of 10% of natural runoff discharges to the Sea for the Nile, Segura, Macta and Almanzora rivers. Other significant water abstraction for large basins is calculated for the Moulouya (77%), Chelif (62%), Ebro (49%) and Orontes (40%). For other large basin, the calculated water abstraction is lower but reach 9%, 13% 24% for the Rhone, Po and Meric. Summing natural and actual discharges, the water abstraction reaches 15% of the natural runoff for the whole Mediterranean drainage basin.

The Mediterranean region is one of the most affected regions in the world by anthropogenic river flow alterations and reservoir management (Döll, Fiedler & Zhang 2009). Agricultural demand is the most important cause of this water abstraction. In the Segura, the total water demand reaches 1.9 km$^3$ yr$^{-1}$ with 87% for agriculture use (CHS, 2008) while calculated runoff is only 0.6 km$^3$ yr$^{-1}$. While irrigation has always existed in the Nile delta, its magnitude has considerably increased, especially since the creation of the Aswan High Dam in 1965 (Nixon 2003) with a 50% decrease of discharge at the delta head. In the Orontes, a 50% decrease of discharge is observed between a Lebanese gauging station and the Syria boundary (ESCWA-BGR Cooperation 2012). In Morocco, after the construction of Mohamed V reservoir, the water discharge at the Moulouya River reduced by about 47% (Snoussi, Haïda & Imassi 2002). Then, nutrient removal or storage due to water abstraction is one of the main drivers of spatial change in nutrient flux. Given these processes commensurate with water abstraction, approximately 15% of the nutrient flux is removed before reaching the Mediterranean Sea.
4.3.2.4 Nutrient storage/removal by instream processes

At the global scale, 13% of the nitrogen emissions is removed by river denitrification (Seitzinger et al. 2006). The denitrification rate is proportional of the average water travel time within basins. Here, we used a first approximation linking basin area with the dissolved nitrogen removal (Dumont et al. 2005):

\[ C_{DIN,\text{instream}} = 1 - (0.0605 \cdot \ln(Area) - 0.0443) \]

The maximum instream retention rate was calculated for the Nile with 85%. For this rate ranges from 60 to 65% for the Rhone, Po, Ebro, Moulouya, Meric and Chelif and approaches 0% for the smallest basins (Figure 41).
4.4 Past change in nutrient concentrations and fluxes

Monitoring programs for large rivers are generally better developed than for small rivers, and water quality data are more easily available. Another advantage is that large river basins integrate the variety of human activities at regional scales, making them more representative than smaller basins. For these reasons, we focus in our trend evaluation first of all at the evolution of the nutrient concentrations in the Rhone, Po and Ebro rivers (Figure 42). For nitrate, concentrations increased steadily from the beginning of the 1970's in all three rivers. Only since the beginning of the 1990s, the values seem to remain at more or less constant concentrations. The increase was more important in the Ebro and Po rivers than in the Rhone River. Also, the annual nitrate loads increased on average in all three rivers. These trends are in good agreement with the situation in other European rivers. At many sites, annual concentrations are approaching a steady state, after two decades of rapid increase. On the basis on linear correlation of the loads and time, it can be estimated that for the 1970s to 1995 period, the nitrate loads increased on average by about 10% per year in the Ebro River. In the Rhone and Po rivers, this increase was about 4% and 5% per year, respectively.

For phosphate, the trends are more diversified. There is also a strong increase of the phosphate concentrations in the Po, Rhone and Ebro rivers at the beginning of the 1970s, even more pronounced than in the case of nitrate. But about 10 to 20 years later, this evolution stops and the values started to decrease again. It is remarkable that in all three rivers, the phosphate concentrations at the end of the 1990s meet again the values that have been encountered at the beginning of the 1970s. When taking the mean of the phosphate loads in the three rivers, one can estimate that phosphate loads from 1975 to 1985 increased on average by about 15% by year. From 1985 to 1995, they decreased again about the initial value. But the evolution is not completely in phase between the three rivers, since the start of the decrease is different. This can be seen best when looking at the phosphate loads. The decline started earliest in the Po river (about 1980), followed than by the Rhone river (around 1985) and finally the Po river (around 1993). Phosphorus concentrations in European Union and Accession country rivers generally declined by 30-40% during the 1990s, with greatest reductions in areas with formerly high phosphorus concentration. Evolution to better water quality was more rapid in Western Europe than in Southern Europe.
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4.5 Main drivers of change in nutrient concentrations and fluxes

4.5.1 Nutrient emissions

For phosphorus (Table 6), the decreasing trend observed in the European rivers could be linked with change in phosphorus emissions in the past decades. While increase in population density was low, point source of phosphorus were largely decreased with the upgrading of wastewater treatment, cleaner technology in industry and interdiction of phosphorus use in detergents. The use of phosphorus in fertilizer also decreased due to adjustments of agricultural practices and increase of the fertilizer costs. In other Mediterranean countries, the demographic evolution and increase of agricultural area, induced an increase of diffuse and point emission of phosphorus. In the total Mediterranean drainage basin, phosphorus emissions increased of $227 \times 10^3$ tP yr$^{-1}$ between 1970s and 2000s. For nitrogen, we also observed a decrease in nitrogen emission for basins of the Tyrrenian, Ionian and Adriatic Seas. However, looking evolution of nitrogen flux for the Po River, this decrease did not induce a decreasing trend for nitrogen flux. This is probably due to the inertia of the hydrochemical response. For the other Mediterranean regions, we observed an increase of both diffuse and point emissions of nitrogen. As for phosphorus, these increased are due to the increase in fertilizer use and population density.

4.5.2 Nutrient storage and removal

As nutrient leaching is controlled by the water discharge within basins, it is likely that decreasing runoff trends for most of Mediterranean Rivers promote a decrease in the nutrient flux.

4.6 Budget and future scenarios for nutrient fluxes

4.6.1 Scenarios

Four MEA scenarios have been implemented in IMAGE for the years 2030s. Each scenario represents a possible socioeconomic development of the world in the near future and is named according to its major characteristics (for a detailed description, see Alcamo et al. (2006)): Global Orchestration (GO), Order from Strength (OS), Adapting Mosaic (AM) and Technogarden (TG). GO depicts a worldwide connected society in which global markets are well developed. Supranational institutions are well placed to deal with global environmental problems. However, their reactive approach to ecosystem management makes them vulnerable to surprises arising from delayed action or unexpected regional changes. OS represents a regionalized and fragmented world concerned with security and protection, emphasizing primarily regional markets and paying little attention to common goods, and with an individualistic attitude toward ecosystem management. AM depicts a fragmented
### Table 7 Diffuse emissions of nitrogen by sea sub-basin for 2000s and 2030s

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### Table 8 Diffuse emissions of phosphorus by sea sub-basin for 2000s and 2030s

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world resulting from discredited global institutions. It sees the rise of local ecosystem management strategies and the strengthening of local institutions. Investments in human and social capital are geared toward improving knowledge about ecosystem functioning and management. TG finally depicts a globally connected world relying strongly on technology and on highly managed and often engineered ecosystems to deliver needed goods and services. Overall, ecoefficiency improves, but it is shadowed by the risks inherent in large-scale human-made solutions. Note that in two of the scenarios, societies generally have a proactive approach to environmental problems (TG, AM), whereas a reactive approach is dominant in the two other scenarios (GO, OS).

4.6.1.1 Evolution of nutrient diffuse emission

In 2000s, the total diffuse emission of nitrogen within the Mediterranean drainage basin is about 12.3 $10^6$ tN yr$^{-1}$. Due to the size of the Nile basin, SLE account for 63% of this total emission. Nitrogen emissions for Northern Mediterranean basins account for 30%. Per unit area, the strongest emissions are in the Northern Mediterranean drainage area, with more than 3000 kgN km$^{-2}$ for NWE, ADR and AEG. Lowest emissions per unit area are observed in CEN. Whatever the scenario, we have an increase of diffuse emissions in 2030s, ranged from 3% (AM) to 23% (GO) for the whole Mediterranean drainage area. In contrast, for the Adriatic drainage area, these emissions decrease for the four scenarios. For the TG scenario, decrease is calculated for all the Northern Mediterranean sub-basin. Per unit area, emissions within SWE drainage area should be the strongest in 2030s and ranged from 3800 to 4200 kgN km$^{-2}$.

For phosphorus, the diffuse emission in 2000s is about 843 $10^3$ tP yr$^{-1}$. SLE accounts for 46% of these emissions and Northern Mediterranean basins for 43%. As nitrogen, emission increase for the four scenarios, with an increase ranged from 26% (AM) to 79% (GO). In the Northwestern, emissions are in a steady state or increase slowly. In the Northeastern and Southern Mediterranean Sea, the emission increase is stronger.
Table 9 Point emissions of nitrogen by sea sub-basin for 2000s and 2030s

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Table 10 Point emissions of phosphorus by sea sub-basin for 2000s and 2030s

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4.6.1.2 Evolution of nutrient emission by wastewaters

For the four scenarios, we obtain an increase in point source emissions of nitrogen and phosphorus in 2030s. For nitrogen, future emissions range from $0.83 \times 10^5$ tN yr$^{-1}$ (OS) to $0.92 \times 10^5$ tN yr$^{-1}$ (TG). For phosphorus, emissions are ranged from $0.16$ to $0.18$ tP $10^6$ tP yr$^{-1}$. These increases are explained by the strong demographic growth for the countries of North Africa in the coming decades. Especially for SLE, including the Nile, emissions are between 25 and 30% of the emissions for the whole Mediterranean drainage area. For NWE and ADR, emissions decrease with the four scenarios for both phosphorus and nitrogen. Expressed per unit area, the highest nitrogen emissions are between $0.95 \times 10^3$ and $1.05 \times 10^3$ kgN km$^{-2}$ for SWE. The low values observed for SLE must be weighted by the location of emissions. Indeed, a large part of point source emissions of nitrogen is due to population within the Nile delta. Emissions in ADR and TYR remain relatively high with values between $0.37 \times 10^3$ and $0.46 \times 10^3$ kg N km$^{-2}$. 
Table 11 Fluxes of dissolved inorganic nitrogen ($10^3$ tN yr$^{-1}$) in 2000s and 2030s scenarios

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Table 12 Fluxes of dissolved inorganic phosphorus fluxes ($10^3$ tP yr$^{-1}$) in 2000s and 2030s scenarios

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4.6.2 Model framework and future budgets

For simulation of the future nutrient fluxes to the Mediterranean Sea, we used the model Global NEWS 2 which has been recalibrated on the basis of our data. Global NEWS 2 is a global, spatially explicit, multi-element and multi-form model of nutrient exports by rivers (Mayorga et al. 2010). NEWS distinguished point sources, which include wastewater emissions from households and industries, and non-point or diffuse sources, including loading of rivers from agricultural land use and natural ecosystems. The NEWS formulation for dissolved inorganic nitrogen (DIN) and phosphorus (DIP) is:

\[ F_{X,\text{river}} = C_{\text{abs}} \cdot C_{X,\text{instream}} \cdot C_{X,\text{res}} \cdot (C_{X,\text{soil/subsoll}} \cdot (F_{X,\text{diffuse}} + F_{X,\text{weathering}}) + F_{X,\text{point}}) \]

All components have been previously described (see 4.3.2). \( F_{X,\text{weathering}} \) is set to 0 for DIN and 26 for DIP. For DIP, \( C_{X,\text{instream}} \) is set to 1. When water discharge and nutrient concentration are available for actual period, modeled values for 2030s are corrected by the ratio between observed and modeled values for actual period and observed values were used for actual period when available.

The total DIN flux for 2000s is about 821 10³ tN yr⁻¹ (Table 11). 31% are discharged in the Adriatic Sea, 20% in the Northwestern Mediterranean Sea and 15% in the Aegean Sea. The Northern Mediterranean Rivers discharge 89% of the total DIN flux. However, for the Nile the modeled DIN flux is zero. As nitrate concentration is about 7 mgN L⁻¹, the DIN flux for the Nile should be stronger than 105 10³ tN yr⁻¹. Then, the total DIN flux is probably closed to 1 10⁶ tN yr⁻¹. For DIP, the total flux to the Mediterranean Sea is about 70 10³ tP yr⁻¹ (Table 12). 27% of the DIP flux is discharged to the Aegean Sea. DIP flux in the Northwestern Mediterranean Sea and the Adriatic Sea are 13 and 14% of the total DIP flux. The Northern Mediterranean Rivers discharge 74% of the total DIP flux.

For 2030s, we computed a decrease in DIN fluxes with the TG (-12%) and AM (-4%) scenarios and an increase for the GO (+2%) and OS (2%) scenarios. For DIP, we computed an increase of fluxes for the four scenarios ranged from +16% for TG and +21% for AM. Whatever the scenario, DIN and DIP fluxes should be lower in the Northwestern Mediterranean Sea and the Adriatic Sea. In contrast, an increase of DIN and DIP fluxes should occur in the Eastern and Southern Mediterranean Sea.
Chapter 5 - Conclusions and perspectives

This inventory has allowed building the most complete dataset on the Mediterranean basin for nutrient concentrations and water discharge in rivers. These data allow estimation of average river nutrient fluxes for many rivers of the Mediterranean basin in 2000s.

However, there are significant gaps. Particularly for Southern Italy, Eastern Adriatic Sea and Greece, we do not have water discharge data after 2000s when we have values for nutrient concentrations in subsequent years. So, nutrient fluxes calculated for these rivers with older values for water discharge could not depict actual values if significant climatic or anthropogenic change occurred in the last decade. For Turkey, we lack data for both nutrient concentrations and water discharge. Data exist but only the inter-annual values are available. It is the same for Eastern and Southern Mediterranean where times series for water discharge are no more updated and only few data for nutrient concentrations are available in the scientific literature.

The two main gaps to assess global nutrient inputs in the Mediterranean Sea are water discharge and nutrient concentration data for the Turkish rivers and the Nile. Despite the very strong decline in water discharge since the construction of the Aswan Dam, the strong population density and intensive agriculture in the delta induce high concentration of nutrient emissions.

To assess regional nutrient inputs, we need water discharge data from 2000s for the Adriatic and Aegean Seas basins and the northern Africa basins. It is necessary to have data of nutrient concentrations and water discharge for nearby or similar stations near the river mouth.

Otherwise many data collected via previous datasets cannot be used to assess a nutrient flux or to consider the value as representative of nutrient inputs in the sea. This is especially true for the Mediterranean where many cities are found along the coast and water withdrawals or urban sewage near the sea can have a significant impact on the basin nutrient budget.

Modeling allows us to estimate the water discharge and nutrients fluxes for rivers without observations for nutrient or water discharge data. While models produce accurate results for water discharge and nitrogen flux, it is important to improve models for phosphorus.

Trend analysis highlight decline of water discharge in the last 50 years. This decline results in largely part to a decreasing trend of precipitation. However, increases in reservoir
capacity and irrigated area are also a driver of this decline. Different climate scenarios show that regardless of change in water use, the water discharge should continue to decline in the coming decades. Demographic growth and intensification of agricultural practices in eastern and southern Mediterranean Sea should induce a larger decrease in this water discharge.

In the Southern Mediterranean Sea, the river water discharge account for only 7% of whole Mediterranean Rivers (3% excluding the Nile). These low inputs suggest a low impact of changes in nutrient fluxes compared to the total river discharge. The Nile is a specific case as it accounts for almost 4% of the water discharge by rivers and as nutrients emissions are very strong closed to the river mouth. Nitrate flux from the Nile is about $105 \times 10^3 \text{ tN yr}^{-1}$, i.e. 11% of total inorganic nitrogen discharge. Given the future trends in agriculture and population for Egypt, the Nile should remain a major river on for nutrient discharged to the Mediterranean Sea.

In the Northwestern Mediterranean Sea and Northern Adriatic Sea, despite low trends for nutrient emissions within basins regarding the other Mediterranean regions, their impact should be stronger as the higher precipitation increase the nutrient leaching from soil to the river mouth. Between these two regions, around the Aegean Sea and Northern Levantine Sea, we have an intermediate situation with a relatively large demographic and agricultural growths and moderate leaching rate of nutrient. Among the four scenarios proposed, Technological Garden is the scenario limiting most of the nutrient export with a decreasing flux of inorganic nitrogen and a low increase of phosphorus flux.
Chapter 6 - References


Chapter 7 - Annexes

Annexe 1 Interannual average runoff and last 20 years runoff for Mediterranean Rivers. Station: name f the gauging station, Area: gauged area (km²), T_all: time coverage for annual river discharge calculation, Q_all: average annual water discharge (km² yr⁻¹), R_all: interannual average of annual runoff (mm yr⁻¹), T_recent: time coverage of the last 20 years annual data, R_recent: average annual runoff for the last 20 years (mm yr⁻¹). Bold values: recent values lower than average on all values.

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¹ http://www.agenciamedioambienteagun.es
² http://hercules.cedex.es/general/default.htm
³ http://aca-web.gencat.cat/sdim/visor.do
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Annexe 2 Nutrient concentration in Mediterranean rivers calculated with available 2000-2010 data series or most recent interannual average (nitrogen: mgN L⁻¹, phosphorus: mgP L⁻¹). NO₃: nitrate, NO₂: nitrite, NH₄: ammonium, DIN: dissolved inorganic nitrogen, DKN: dissolved kjeldall nitrogen, DON: dissolved organic nitrogen, TDN: total dissolved nitrogen, DIP: dissolved inorganic phosphorus, TP: total phosphorus

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¹⁰ http://www.juntadeandalucia.es/medioambiente/site/rediam/
¹² http://www.chj.es/es-es/medioambiente/redescontrol/Paginas/RedesdeControl.aspx
¹³ http://aca-web.gencat.cat/sdim/visor.do
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Annexe 3 Nutrient fluxes by Mediterranean rivers calculated with available 2000-2010 data series or the most recent interannual average for nutrient concentration, and with interannual average of water discharge computed with last 20 years data series or most recent interannual average (nitrogen: tN yr⁻¹, phosphorus: tP yr⁻¹). NO₃: nitrate, NO₂: nitrite, NH₄: ammonium, DIN: dissolved inorganic nitrogen, DKN: dissolved kjeldahl nitrogen, DON: dissolved organic nitrogen, TDN: total dissolved nitrogen, DIP: dissolved inorganic phosphorus, TP: total phosphorus

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Annexe 4 Specific nutrient fluxes by Mediterranean rivers calculated with available 2000-2010 data series or the most recent interannual average for nutrient concentration, and with interannual average of water discharge computed with last 20 years data series or most recent interannual average (nitrogen: kgN km² yr⁻¹, phosphorus: kgP km² yr⁻¹). NO₃: nitrate, NO₂: nitrite, NH₄: ammonium, DIN: dissolved inorganic nitrogen, DKN: dissolved Kjeldahl nitrogen, DON: dissolved organic nitrogen, TDN: total dissolved nitrogen, DIP: dissolved inorganic phosphorus, TP: total phosphorus

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