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The overlooked impacts of freshwater scarcity on oceans as evidenced by the Mediterranean Sea

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Water stress is an urgent issue in many regions worldwide, particularly in southern European countries. This study reveals the consequences of decreased freshwater flow on marine ecosystems in the Mediterranean Sea due to climate change and escalating water demands. A 41% reduction in river flow may result in a 10% decline in marine primary productivity and a 6% decrease in biomass of commercial fish and invertebrate species. Regional reductions could be as high as 12% and 35%, disrupting coastal and marine ecosystems and their related socio-economic sectors. The findings emphasize the importance of considering nutrient load changes in water management strategies and incorporating marine ecosystem requirements into environmental flow requirements for freshwater bodies. Integrated, source-to-sink management approaches are crucial for sustainable water resource utilization.

Water demand for different human uses and its pollution is putting pressure on natural water availability. According to recent estimates of water stress in Europe, droughts and water scarcity in general have become a common occurrence with reports indicating that around 20% of the entire European territory and 30% of the European population experience water stress (https://www.eea.europa.eu/themes/water/glossary/water-stress) every year[1–3]. The impacts of climate change are expected to exacerbate the situation, particularly in southern and south-western European regions, where river discharge could decrease by up to 40% by 2050[4] and to a greater extent with increasing global warming levels towards the end of the century[1,5,6]. In the absence of climate mitigation action (4 °C in 2100 and no adaptation), annual drought losses in the European Union and the United Kingdom combined are projected to rise to more than €65 billion per year compared with €9 billion per year currently[7].

Given the increasing prevalence of water stress (i.e., the inability to meet the demand for water) and water scarcity (i.e., the lack of abundance of water)[8], there is a growing recognition across European communities and industries of the need for alternative water sources, such as desalination and water reuse[9–11]. This trend has been particularly noticeable in southern Europe, where the agricultural and tourism sectors are the most important water consumers but are also vital to the regional economy.

Water scarcity spurs competition, if not outright conflict, between agricultural, industrial, domestic, and environmental uses of water. Integrated Water Resource Management (IWRM) principles have been developed to address this challenge by ensuring the sustainable and equitable management of water, land, and related resources. This approach considers social, economic, and environmental needs to protect water quality, availability, and allocation[12,13].

Recently, the IWRM concept has evolved into the Water-Energy-Food-Ecosystems (WEFE) Nexus, which expands the scope beyond water to include food and energy security considerations[2,3,14]. In IWRM and the WEFE Nexus, the water needs to sustain land –including

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aquatic- ecosystems are usually accounted for through the establishment of "ecological" or "environmental flow requirements" (e-flows)[3,15]. The importance of freshwater flow to coastal ecosystems is acknowledged by long-standing EU legislation, including the Urban Waste Water Treatment Directive (UWWTD) (Council Directive 91/271/EEC) and the Water Framework Directive (WFD, 2000/60/EC), which recognise the concept of e-flow as also applicable to the receiving marine/coastal environments.

The ongoing debate regarding water scarcity and the management and prioritisation of its uses by different industries and activities fail, however, to consider the role freshwater flows play in maintaining vital coastal ecosystems. Freshwater reaching the ocean is often regarded as 'wasted' or 'lost' rather than used to benefit inland applications/activities. Even if coastal and marine stakeholders may be represented in or addressed by the authorities competent for river basin management plans in the EU, the interaction between freshwater and marine ecosystems is often regarded as limited to water quality or, at best, the supply of sediments to coasts, with little consideration for freshwater flows[16].

Extensive research has demonstrated that flowing freshwater plays a crucial role in connecting and influencing both land-based and marine-based ecosystems[17–19]. Any alteration in the quantity or quality of these waters will invariably affect not only land-based activities and riverine ecosystems but also marine ecosystems, especially coastal areas[20,21], driving near-coastal circulation[22,23] and discharging nutrients at the basis of primary production[24]. Furthermore, freshwater inputs are essential drivers for spawning and nursery areas that sustain many commercially important species in coastal ecosystems[25,26].

This study employs the Blue2 Modelling Framework (Blue2MF), developed at the Joint Research Centre (JRC) of the European Commission[27–29], to assess the multifaceted impacts of a substantial reduction in freshwater flow into the Mediterranean Sea basin. The analysis is specifically designed to investigate the impacts on biogeochemistry, the upper food web, and the socio-economic implications for the Mediterranean Blue Economy. Blue2MF, a comprehensive suite of modelling tools, is adept at examining the implications of various management and policy options on marine ecosystems, including the interconnections between inland and marine waters[30].

The study focuses on the Mediterranean Sea for several reasons. Firstly, this basin has been identified as a hotspot for climate change[31] owing to its semi-enclosed nature, located in mid-latitudes. Secondly, for certain periods of the year, water exploitation in the Mediterranean basin is currently at almost 100%[2]. Further reductions in precipitation resulting from climate change predicted for this region, would considerably reduce freshwater availability in the future[32,33]. Finally, it has been established[21] that riverine inputs are critical drivers for the primary productivity of key areas of the Mediterranean Sea, with the abundance of some commercially important species linked to the freshwater fluxes into the basin[34].

Being a semi-enclosed basin, the Mediterranean Sea is strongly influenced by land in many different ways. Its general circulation is anti-estuarine, with the inflow of fresher waters from the Atlantic and the outflow of denser Mediterranean waters created by excess evaporation over rainfall plus riverine inputs[35,36]. This water interchange drives the overall circulation of water in the basin[37] together with wind forcing, riverine flow and the topography (e.g., the intense cyclonic circulation within the Adriatic Sea[38]). This water circulation plus riverine inputs determine the particular nutrient conditions of the basin where the nitrogen to phosphorus ratio (N:P) is much higher than in the general ocean[39], creating particular conditions for phytoplankton growth[40] and general oceanic production[41,42].

Results

Impacts on the biogeochemistry

The application of the extreme (EXT) water reduction scenario (described in Methods) corresponds to a reduction of freshwater flow into the Mediterranean Sea to 41% of its reference value (REF scenario, Fig. 1a) in line with other future estimates[4,33], and with a relatively uniform distribution of the reduction across the whole basin (Fig. 1b). The impacts on the biogeochemical conditions (i.e., primary production indicators) of the marine ecosystem, however, vary considerably between different regions.

Primary production in marine ecosystems forms the foundation of the food web, generating energy and organic matter that sustains the entire food chain. The most noteworthy reductions in primary productivity indicators, such as Chlorophyll-a (Chla) (Fig. 2a) and primary production rate (PPR) (Fig. 2b), are mainly expected in the semi-enclosed Adriatic and Aegean basins (Fig. 3), with mean reductions of approximately 30% (Supplementary Information Table 1), but with maximum values exceeding 40% in river plume areas. This is in agreement with the recently reported impacts of river flow reduction in Adriatic ecosystems[43]. In addition, there is a substantial reduction (−18% on average, Supplementary Information Table 1) in carbon export (i.e., the carbon transferred below the euphotic zone) in those two sub-basins (Figs. 2c and 3). The fundamental role in marine biogeochemistry and ecology of exported carbon is twofold: (i) it provides energy to benthic and mesopelagic communities and (ii) a fraction of this carbon is sequestered for climatically relevant time scales into deep waters and/or sediments[44]. This means that the decrease in exported carbon might substantially modify the structure and function of the whole marine ecosystem[45].

The Adriatic and Aegean Seas are both regions of relatively high productivity (Supplementary Information Fig. 1)[40] highly influenced by riverine conditions[21,35], which explain the important impacts of the freshwater reduction scenario on their biogeochemical conditions. The overall Mediterranean Sea and the North-western region of the basin show less marked, but still negative, changes in biogeochemical indicators (Figs. 2 and 3), suggesting that reduced freshwater flow into the basin will likely lead to a decrease in the overall marine productivity (see also Supplementary Information Table 1), and in particular in the coastal areas.

The simulated regional differences are linked to the relative importance of external (riverine) versus internal (oceanographic mixing) nutrient inputs[46]. In some areas, such as the North-western Mediterranean, the influence of large rivers like the Ebro and Rhone affects the biological conditions of nearby marine waters[21,47,48]. However, strong oceanographic features, such as the slope-attached Northern Current and intense winter deep convection mixing, supply substantial nutrients to the photic layer and govern the overall productivity of the region[49–52]. Conversely, regions like the Aegean Sea, devoid of large rivers, exhibit a strong dependence on allochthonous nutrient fertilisation[21,46] due to the relatively lower relevance of oceanographic processes in transporting nutrients to the photic layer.

As described in Methods, one additional scenario was performed considering the same amount of water flow reduction but maintaining the total loads of nutrients to the sea (the NUTS scenario). In this scenario, the decrease in biogeochemical indicators is less acute than in the EXT scenario for all regions (e.g., −13% in the Adriatic and −5% in the Aegean for Chla and PPR, Supplementary Information Fig. 2, compared to about −28% and −35%, respectively, Fig. 3). The correlation coefficient between the decreases in biogeochemical indicators in both scenarios (Supplementary Information Fig. 3) is high (0.78 for Chla and 0.66 for PPR) and significant (p-values < 0.01), indicating that the affected areas are mostly the same in both cases. The slope of the correlations is smaller than 1 (Supplementary Information Fig. 3), as areas little impacted show similar values in both scenarios while the

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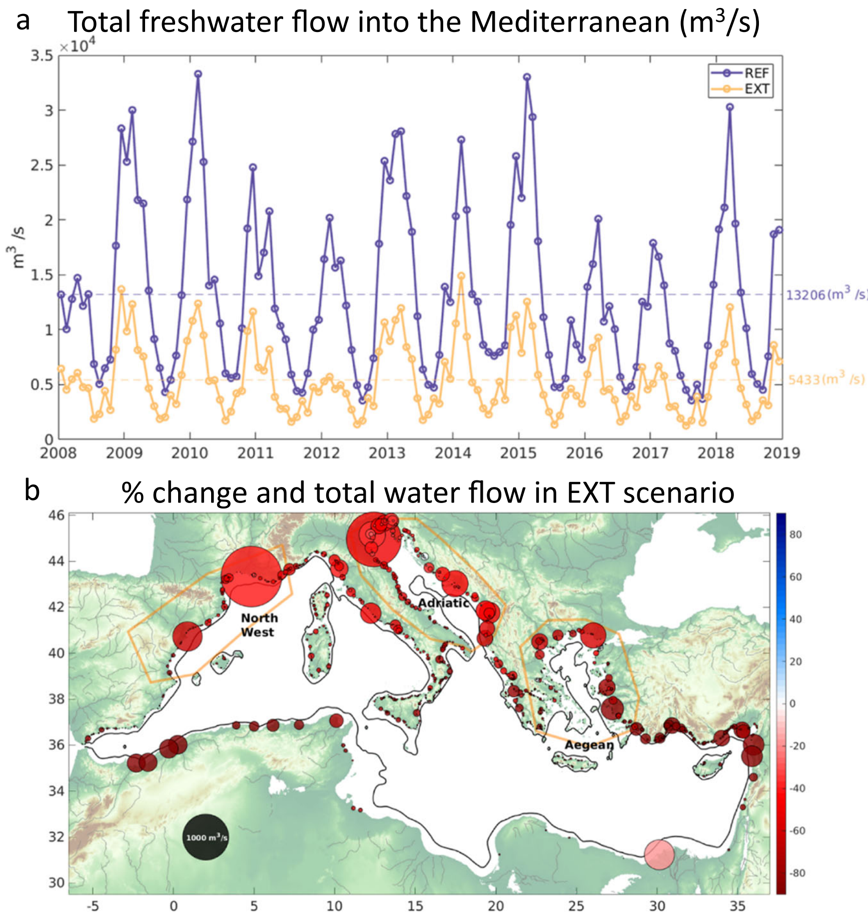

Fig. 1 | Freshwater scenarios. a Time series of freshwater flow in the reference (REF) scenario (blue line) and in the extreme (EXT) water reduction scenario (yellow line). **b** Percentage change of the freshwater flow in the EXT scenario for all the rivers included in the modelling setup (colour of the circle) and mean flow value for the individual rivers (size of the circle). The thin black line shows the 150 m isobath, while the orange polygons indicate the regions averaged for the different sub-basins. Figure created by the authors using Matlab.

bigger differences happen in the most impacted regions. These results show that the negative impacts of the EXT water-reduction scenario, including both the reduction of water flow and the total loads of nutrients, are substantially more important for marine ecosystems than those of the NUTS scenario where only the water flow is reduced. This suggests that nutrient loads must be accounted for when analysing water flow reduction in the marine environment.

Impacts on the food web

The modifications in the biogeochemical conditions of the Mediterranean marine ecosystems impact the related global structure and function of the food webs, as predicted by the high trophic level (HTL) model of the Blue2MF[53], with an overall decline of biodiversity, as expressed by a 1.8% (± 0.9%) reduction of the Shannon Diversity Index, across the entire Mediterranean Sea under the EXT scenario (Supplementary Information Fig. 4).

In this study, however, we aim to focus on selected few ecosystem state indicators, particularly those directly linked to fisheries activities, such as commercial fish and invertebrate species' biomasses (see "Methods").

Similarly to the changes in primary productivity indicators, the biomass of commercially important fish and invertebrates shows an overall reduction across the Mediterranean Sea (Supplementary Information Table 2), particularly in the Adriatic and Aegean Seas (Fig. 4 and Supplementary Information Fig. 5). For commercial fish, the decline is estimated at approximately −2.5% for the Mediterranean Sea, whereas for both the Aegean and the Adriatic Seas, the reduction is of about −11% (Fig. 4 and Supplementary Information Table 2). An analogous pattern was predicted for commercial invertebrates in the Aegean Sea with values exceeding −12%, but a lower reduction in the Adriatic Sea (−4%) and a higher reduction of −6.5% in the whole Mediterranean Sea (Fig. 4 and Supplementary Information Table 2).

At the species level, differences can be observed for both assessed fish and invertebrate groups. Among the fish, the pelagic Bluefin tuna (−20%) and the mackerels (−13%), followed by the demersal European hake (−8%) appear to be the most negatively impacted species. For the invertebrates, the Blue and Red shrimp and Giant Red shrimp displayed the highest biomass reduction (−14%). Similarly to the biogeochemical indicators, the mean biomass of commercial species (both fish and invertebrates) in the REF situation is substantially higher in shallow/coastal areas and in the most affected sub-basins (Adriatic and Aegean) than in the open sea areas (Supplementary Information Fig. 6).

Coasts and shelves are normally characterised by high levels of primary production and by physical (e.g., depth) and environmental (e.g., temperature, salinity) properties[54,55] that favour high concentrations of fish/invertebrates[56], as in this case. The Adriatic and the Aegean seas, in particular, compared to other Mediterranean areas, are driven by high productivity coming from river run-offs, which, thanks also to the semi-enclosed nature of these basins, sustain a high level of biomass of HTL organisms, and high exploitation[53,57,58] (Supplementary Information Fig. 9).

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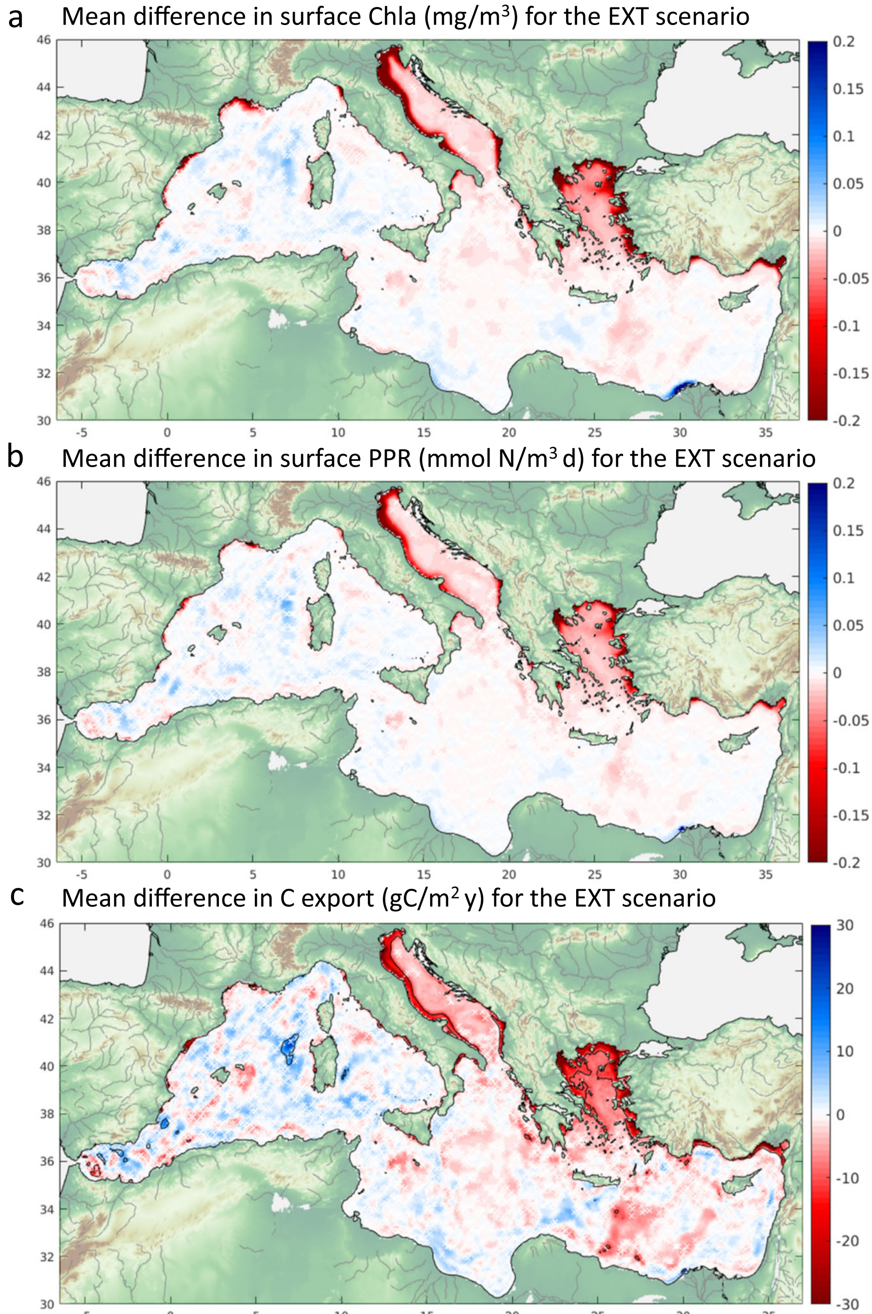

Fig. 2 | Biogeochemical impacts of EXT scenario. Biogeochemical impacts. Mean differences in (**a**) Chlorophyll concentration, (**b**) Primary Production Rate, and (**c**) Carbon export between the reference (REF) and the extreme water reduction (EXT) scenario. No significant differences (C.V. in reference simulation > % difference) are blanked out. Carbon export has been estimated from the Primary Production Rate (assuming a C:N ratio of 106:16), applying the empirical relationships suggested by Eppley and Peterson (1979). Figure created by the authors using Matlab.

Testing the robustness of model results with independent Earth observation data

While the elements of the Blue2MF models have been extensively validated in previous publications (see details in "Methods"), it is important to assess the sensitivity of the model to changes in forcing. In this case, the response being evaluated is the abundance of commercial species, and the forcing is the freshwater flow from rivers. Although there was no similar year in the available record (2008–2018) to the simulated EXT scenario for the entire Mediterranean Sea, the observed conditions of 2022 are at the level of the EXT scenario in the Adriatic Sea (see Supplementary Information Fig. 7). The main river in the region, the Po, had extremely low values for that year within the range of the expected flow in the tested EXT scenario. Therefore, comparing the difference in fish productivity between 2022, as an equivalent of the EXT scenario, and the REF years (2015–2018) in the Adriatic should suitably reproduce the effects of scenario differences provided by the model in that area.

The robustness of the model results on commercial fish production was therefore tested using an independent spatio-temporal index of potential fish production, the Ocean Productivity available to Fish (OPFish, see "Methods" and Supplementary Information Fig. 10). Modelled values of commercial fish abundance in the Adriatic (yellow stars in Supplementary Information Fig. 8) show a significant correlation ($R = 0.61$, $p < 0.01$) with the OPFish normalised values (red squares

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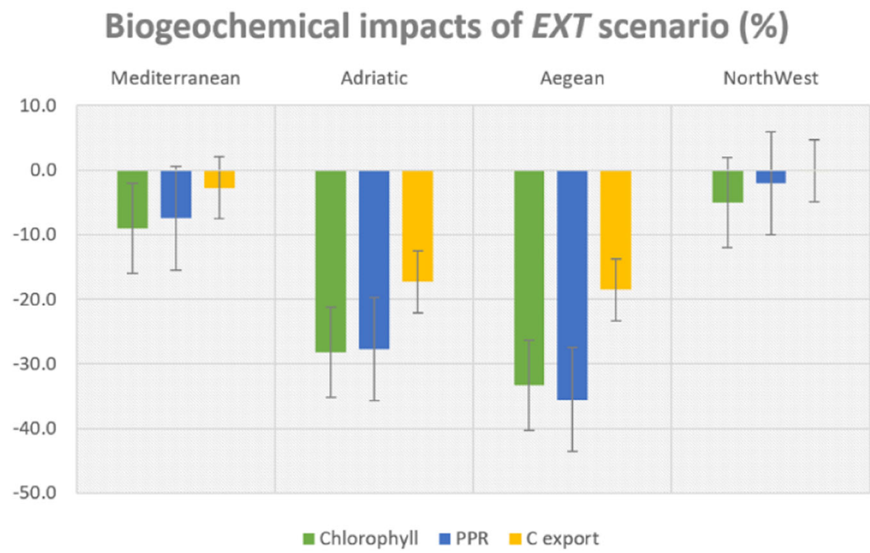

Fig. 3 | Integrated biogeochemical indicators changes. Percentage reduction for the biogeochemical indicators in the extreme (EXT) scenario compared with the reference (REF) simulation for the different regions (whole Mediterranean, Adriatic Sea, Aegean Sea and Northwestern Mediterranean). Error bars indicate the inter-annual variability in the differences.

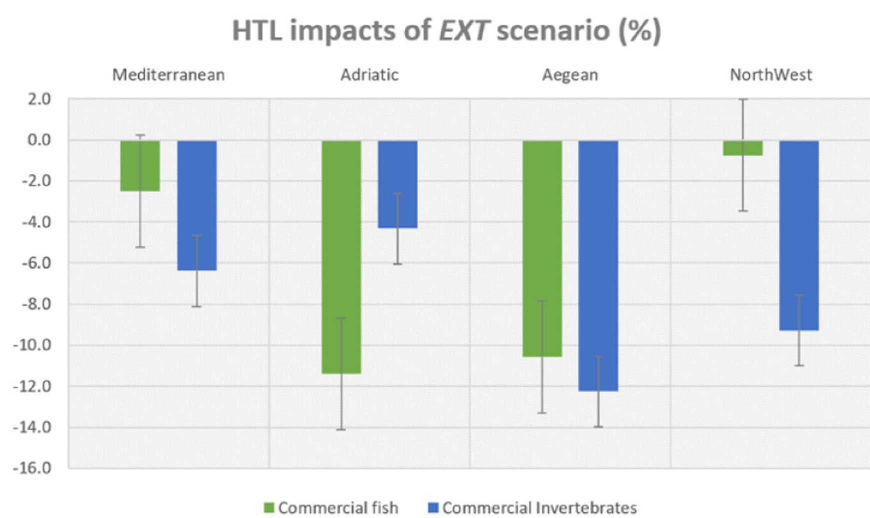

Fig. 4 | Integrated commercial species changes. Percentage reduction for the commercial species biomass (fish and invertebrates) in the extreme (EXT) scenario compared with the reference (REF) simulation for the different regions (whole Mediterranean, Adriatic Sea, Aegean Sea and Northwestern Mediterranean). Error bars indicate the inter-annual variability in the differences.

in Supplementary Information Fig. 8, normalisation over the period 2003–2022) for the REF period (2015–2018) with similar inter-annual variability. This indicates substantial model sensitivity to the changes in forcing. Furthermore, the difference of the mean OPFish values in the Adriatic Sea between the 2015–2018 period (representative of the REF simulation, red line in Supplementary Information Fig. 8) and its value in 2022 (representative of the EXT conditions, red rhomboid in Supplementary Information Fig. 8) of −12.2% is consistent with the EXT-REF modelled difference in commercial fish biomass for this basin (−11.4%, see Supplementary Information Table 2).

Social and economic impacts for the Mediterranean Blue Economy

Fishing intensity is highest along the coastal strip of the Mediterranean Sea (Supplementary Information Fig. 9), particularly in the Adriatic Sea where commercial species biomass is typically higher (Supplementary Information Figs. 6 and 10). The comparison of the environmental changes of the EXT scenario indicated by the Blue2MF (Fig. 2 and Supplementary Information Fig. 5) with the fishing density distribution (Supplementary Information Fig. 9) clearly highlights that the negative impacts on biogeochemical productivity indicators and fisheries resources primarily arise in intensively fished regions (Fig. 5). It was estimated that fishing density is about one order of magnitude greater in regions experiencing negative impacts (0.4 boats/km^2) than in those areas where changes are expected to be neutral or beneficial (0.04 boats/km^2). It must be noted that fishing intensity data (Supplementary Information Fig. 9) does not include non-EU fishing fleets so the comparison above is not encompassing the whole basin.

The spatial coherence between predicted changes in overall marine productivity and fisheries activities implies that water flow reduction will have a direct impact on the fishing industry and coastal communities. Estimations of biomass losses in commercial fish and

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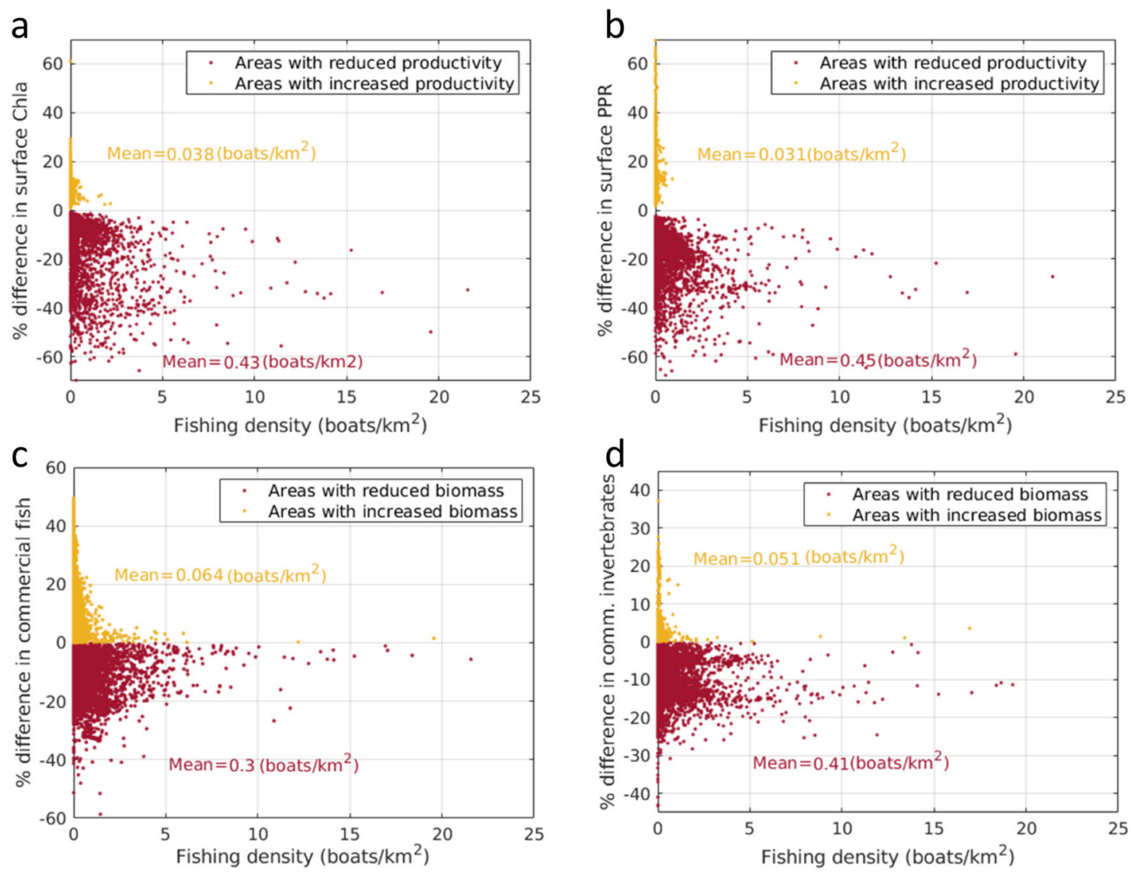

Fig. 5 | Environmental changes with respect to fishing intensity. Fishing density (boats/km2) from the EMODNet dataset (2015–2018) versus the % change in biogeochemical conditions (**a**: Chla and **b**: PPR) and commercial species biomasses (**c**: fish and **d**: invertebrates). Increases in biological indicators are designated with yellow dots and decreases with red dots.

Table 1 | Potential economic loss for fisheries because of the reduction in commercial species in the extreme (EXT) freshwater reduction scenario

Region	Comm. fish loss (Billion €/y)	Comm. invert. loss (Billion €/y)	Total loss (Billion €/y)
Mediterranean	−0.86	−3.85	−4.70
Adriatic	−0.43	−0.17	−0.60
Aegean	−0.37	−0.74	−1.11
NorthWest	−0.02	−0.35	−0.37

invertebrates (Supplementary Information Table 3) are about 25–30% of the current overall fish landings and about 3 times more than the overall invertebrate landings in the Mediterranean Sea[59]. The highest proportional impacts will be concentrated in the most intensively fished regions, such as the Adriatic and the Aegean Seas (Supplementary Information Fig. 9). In both regions, the biomass loss would be larger than the current fisheries landings. Given the already over-exploited status of most fish stocks in the Mediterranean Sea[60], such biomass losses could easily lead to disruptions in the structure and functions of coastal and marine ecosystems, annihilating the current efforts of fisheries management to reduce overfishing and destabilise even more the fisheries sector.

These biomass losses (Supplementary Information Table 3) can be converted into potential economic losses by assuming an average first-sale price for fish of 3€/kg and 7€/kg for invertebrates[61,62]. Across the entire Mediterranean basin, this potential loss in biomass would amount to almost 4.7 billion € per year (Table 1), implying a big shock for the Mediterranean fisheries sector. Considering that the EU has about 65 thousand fishers in the Mediterranean Sea landing about 1.9 billion € per year of catches[63], the employment and Gross Value Added (GVA) generated across the value chain (e.g., fish processing, wholesale, retail) is between 2.5 and 4 times larger than the catching sector[63]. Hence, the potential impacts of this important loss in biomass would easily go beyond a mere reduction in fisheries landings, disrupting coastal and marine ecosystems and damaging the viability of the fisheries sector as well as related economic sectors and coastal communities.

The EXT water scenario tested here can also considerably affect other ecosystem services, such as the Mediterranean Sea's capacity to export carbon that could decrease by nearly half a million tonnes per year (Supplementary Information Table 4), which represents −3% at basin level but up to −18% at regional level (Fig. 3). This loss of exported carbon will inevitably reduce the carbon sequestration within the basin, potentially hampering the achievement of climate neutrality prescribed by the European Green Deal (COM (2019)640), contributing to the disruption of marine food webs[45] and lowering their resilience to climate variability.

Discussion

The outcomes derived from the Blue2MF simulations suggest that a substantial decrease in freshwater inflow can significantly impact the Mediterranean marine ecosystems. This study reveals that the magnitude of these changes varies across regions depending on their geomorphology and freshwater inputs but, overall, an important decline in marine primary productivity can be expected, in turn affecting the higher trophic levels.

The most productive regions, largely driven by freshwater inputs, are also the most intensively fished areas likely to be highly affected by the runoff reduction with a substantial decrease in marine productivity and available fisheries resources. This has the potential to disrupt the regional ecosystems and severely affect the fisheries sector and the associated economic activities of the coastal communities. Our results underscore the urgent need for a comprehensive and integrated approach to water resource management within the European Union.

We acknowledge that the selected EXT scenario (considering no changes in nutrient concentrations) represents a simple and potential worst-case outcome derived from climate change and increasing water demand and that this exercise is not a detailed projection of what could occur in the coming decades. The limitations of the tested scenario stem as well from the assumptions of unaltered fishing effort and external (e.g., atmospheric) forcing, which would unavoidably impact fish productivity in the future.

Another important uncertainty source lies in the assumed nutrient concentrations in the rivers (e.g., the EXT and NUTS scenarios). Likely, the future freshwater nutrient load will be between those two extremes, where exactly is highly uncertain. Henceforth, exact numbers derived from our analysis should not be considered as a quantitative assessment of potential future conditions in the Mediterranean Sea, but rather as a likely order of magnitude of the impacts on the marine ecosystems and it is used with the aim of raising awareness on the need to consider them as resulting from an unbalanced and unsustainable management of freshwater.

In our study, our primary focus lies on the Mediterranean Sea; however, the issue of water flow reduction due to climate change extends beyond this basin. Water abstractions are projected to increase globally[64] coinciding with an anticipated acceleration of the water cycle under high-emission climate scenarios[65]. This combination may result in increased river flow in some regions and decreased flow in others, as demonstrated in various parts of the world[66–68]. Consequently, the compounding effects of climate and socio-economic changes are anticipated to lead to water scarcity in specific regions[69], which could ultimately impact local marine waters and ecosystems.

To effectively address these challenges, it is crucial to adopt a holistic perspective from source to sea that considers the needs of multiple social sectors while ensuring the resilience and conservation of ecological resources and services in freshwaters, coastal and marine adjacent regions. This requires the implementation of sustainable practices towards adaptation that balances human activities with the preservation of all water resources and aquatic ecosystems. Future research should address the likely reductions of water and nutrients under sustainable practices considering, as well, the direct impacts of climate change on nutrient delivery pathways and marine hydrodynamics (e.g., stratification, currents).

As a note of caution, the underlying hydrodynamic model used in the Blue2MF framework has been designed to represent the whole oceanic basin. While their relatively high spatial resolution of 9 km permits to represent the complexity of oceanic structures at mesoscale, its ability to address local impacts (e.g., specific estuaries or specific parts of coastal regions) is limited. This limitation should be considered in future investigations using appropriate modelling tools such as coupled models of different resolutions or of variable mesh resolution.

The findings of this study emphasise the need for proactive measures to mitigate the potential negative impacts of reduced freshwater inflow on marine ecosystems in the Mediterranean Sea and wherever water availability is at threat. These measures should include the development and implementation of adaptive management strategies ensuring their long-term resilience and the preservation of the vital services they provide to both the environment and society.

Methods

The Blue2 modelling framework

The Blue2 modelling framework (Blue2MF) is a comprehensive suite of modelling tools designed for simulating EU marine ecosystems under a variety of management and policy scenarios[27]. More specifically, Blue2MF has been extensively employed to simulate biogeochemical characteristics, both during hindcast periods[34,53] and for forecasting future conditions[49,70] in the Mediterranean Sea. It has also been applied to investigate High Tropic Levels (HTL) conditions in this basin[28,40,71]. Blue2MF is constituted of different components summarised below.

Those different modelling components are linked to each other either offline (i.e., the results of one model are the inputs to the next) or online (i.e., they are integrated at the same time). In all cases, however, the external forcing and conditions (e.g., the atmospheric conditions) are identical to all models to ensure consistency in the tested scenarios.

Freshwater model: This framework simulates the freshwater conditions of EU rivers and lakes regarding their quality (nutrient concentration) and quantity (water flow). More specifically, the freshwater nutrient levels are computed by the Geospatial Regression Equation for European Nutrient losses (GREEN) hydrological model[72]. GREEN includes a geospatial data model for Europe, where data are linked to the hydrological structure of the river network to model nitrogen and phosphorus flow in the river basin according to different pathways. Europe is divided into c.a. 1 million catchments of 7 km^2 average size. In complement, GREEN incorporates the freshwater flux from the LISFLOOD model[73]. The freshwater flux and nutrient loads at the land / sea interface are used as inputs by the hydrodynamic and biogeochemical ocean model.

For computational reasons, very small rivers (mean flow < 5 m^3/s) or those that seasonally disappear are not included in the modelling framework. This implies the elimination of a number of rivers, particularly on the northern African coast, but the nutrient loads from those rivers are not strongly relevant for the marine ecosystems, except maybe very close to the estuarine outlet (which, anyhow, is beyond the hydrodynamic model resolution, see below).

Hydrodynamic and biogeochemical Ocean model: The hydrodynamic component of Blue2MF is the General Estuarine Transport Model (GETM)[74]. This configuration permits a realistic description of the whole Mediterranean Sea[34,40,49,70] in a 3D manner. The spatial resolution is about 9 km in latitude and longitude. It comprises 25 terrain-following (sigma) vertical layers. 6-hourly atmospheric fields originating from reanalyses or climate projections are used to force ocean circulation. The Mediterranean Ecological Regional Ocean Model (MedERGOM)[49] has been interactively coupled to the hydrodynamic model. MedERGOM includes seven compartments, describing the ocean biogeochemistry (nitrate, phosphate, detritus) and the lower trophic levels of the ecosystem (3 phytoplankton functional types, 1 zooplankton).

The freshwater inflowing from the rivers is first added to the ocean model grid boxes representing the river mouth, thereby reducing the salinity in these grid boxes. Then the properties (salinity, temperature, nutrients) of the grid boxes are treated as normal model tracers, consequently advected mainly by the horizontal currents and dispersed by horizontal and vertical diffusion. When applying appropriate numerical methods, these processes represent the spreading of river plumes in a suitable way[75].

High Trophic Levels (HTL) Ocean Model: The HTL are simulated using Ecopath with Ecosim (EwE[76]) which captures the structure and the dynamics of the marine food webs. A specific configuration has been set up for the Mediterranean Sea[53]. The HTL component uses the physical (i.e., temperature, salinity) and biogeochemical (i.e., phytoplankton biomass) fields generated by the coupled hydrodynamic-biogeochemical model.

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The HTL model simulates the trophic links across groups of species that represent the main pathways of the energy flows in the ecosystem and is used to assess temporal and spatial changes in ecosystem biodiversity. The trophic relationships within primary producer groups are resolved by the biogeochemical model. MedERGOM simulates three different phytoplankton types: cyanobacteria, small phytoplankton and large phytoplankton, each with its own functions and physiological dependence on environmental variables. Only small and large phytoplankton biomasses are 'transferred' to the HTL, with independent paths along the food chain. Cyanobacteria biomass is not used by the HTL model as there are no predators for this type of food web. The Shannon index[77] is commonly used in ecological studies as a composite metric representing both species evenness and species richness. Applied to EwE, however, where functional groups substitute for individual species, and the number of functional groups is generally fixed, the index permits the describe functional group evenness, which represents the biomass distribution across functional groups (maximum evenness is achieved when all functional groups have equal biomass).

The commercial fish and invertebrate biomass index is calculated as the sum of the biomass only for those groups in the model having a commercial value (unit: t/km^2). The groups of fish included are: commercial pelagics (large, e.g., tunidae; medium, e.g., scombridae; small, e.g., Clupeidae) and commercial demersals (large, e.g., Gadidae; medium, e.g., Sparidae; small, e.g., Mullidae), rays/skates/turbots and demersal sharks. Commercial invertebrates include decapods such as shrimps, crabs, lobsters, bivalves and cephalopods (e.g., squids, cuttlefish and octopus). The specific commercial species included in the model are detailed in a previous study[53].

Reference scenario

The reference conditions (REF) for the Mediterranean Sea are obtained from a simulation performed between 2008–2018, utilising atmospheric conditions sourced from reanalysis products (ERA5) and the most reliable estimates of riverine inputs (both quantity and quality)[78]. To avoid any impact from the initial conditions, biogeochemical variables are extracted for the period 2015–2018 as representative of the reference situation in this timeframe. Forcing Blue2MF models with those riverine conditions provides a realistic description of the past and present biogeochemical and ecosystem characteristics in the basin[28,29,71].

Water availability scenarios

The reference scenario (REF) is compared with alternative scenarios that consider a reduction in freshwater only (constant nutrient total loads, NUTS) and of both freshwater and nutrient loads (EXT) reaching the river outlet. All other factors, including the climatic conditions, are the same for all scenarios. The alternative scenarios described below represent a situation where freshwater is extracted from the catchment and used before it reaches the marine environment.

The water quantity component of Blue2MF, the LISFLOOD model, is used to provide an estimation of the river streamflow projections at the coastal outlets into the Mediterranean. Therefore, river streamflow projections with global warming are obtained by forcing LISFLOOD with an ensemble of 11 bias-corrected regional climate projections from EURO-CORDEX[79] from 1981–2100. For future projections, the Representative Concentration Pathways RCP 8.5 emission scenario is considered. The estimation of the future river flows is set on a 30 yr window around the year that global warming reaches 4 °C above pre-industrial temperature. For models that have a warming of 4 °C later than 2085, the period 2071–2100 is taken. The period 1981–2010 is then used as a reference to obtain the relative change in monthly mean river streamflow. The river flow in the 30-year ENSEMBLE mean is around 91% of the REF value with both positive and negative streamflow changes for individual river outlets.

However, as our aim is to test the impacts of an extreme flow reduction scenario, we reduced the values on the ENSEMBLE mean by an additional 50% (91–50%), i.e., a 41% flow level of the 2008–2018 level, for every outlet in the Mediterranean Sea (Fig. 1). This extreme 'low flow' scenario is constrained such that the total reduction in individual rivers streamflow compared to the reference scenario cannot exceed the upper threshold of 90% as we assumed that it is unlikely to deplete a river completely. While this study adopts an extreme approach, it is data-driven (based on the ENSEMBLE mean), aiming to maintain the nonlinear behaviour of the river streamflow dynamics into the Mediterranean Sea.

Although the extreme 'low-flow' is dramatic, it is realistic for individual catchments as shown in Supplementary Information Fig. 7 where the values of the scenarios are compared with the observed streamflow in one of the largest (Fig. 1b) and most influential Mediterranean rivers for its oceanographic conditions, the Po river[21,43]. The mean annual flow observed in the Po river mouth (obtained from the regional environment agency of Emilia Romagna at https://simc.arpae.it/dext3r/) for the period 2001–2023 is very similar to the value provided by LISFLOOD for the REF scenario (1353 m^3/s vs. 1392 m^3/s) (Supplementary Information Fig. 7). The flow value calculated in the 'low-flow' scenario for the Po (orange line in Supplementary Information Fig. 7) is 51% of the REF value (713 m^3/s). In the 23 years of observational data, there are at least 5 instances in which the flow is within the 'low-flow' value confidence range (discontinuous orange lines in Supplementary Information Fig. 7) with the year 2022 showing a considerably lower flow as never seen before and part of a long-term trend in increasing drought events both in frequency and severity[80].

In the context of unbalanced water management, the extreme 'low flow' scenario presented in our study could potentially result from a large fraction of the surface-flowing freshwater being abstracted and consumed before reaching the coastal region. This scenario might serve as a compensatory factor for the absence of certain elements in Earth System Models projections[81], which could make streamflow decline more severe than estimated in the ENSEMBLE scenario.

It should be noted that, in the scenario, we assume direct abstraction of the flowing waters and no alteration of the chemical properties of the remaining river flow. This scenario ('low flow' + constant nutrient concentration) is named the EXT scenario in the context of this investigation. A major assumption in this EXT freshwater scenario is, thus, the sustained nutrient concentrations in flowing waters (which implies a reduction in the nutrient loads).

In reality, when water is withdrawn from rivers for terrestrial use, a portion of it typically returns to the rivers with a different chemical composition, leading most likely to an increase in nutrient concentration. The exact nutrient concentration in the reduced flow scenario is challenging to calculate, but it must be constrained by a minimum (i.e., the value in the EXT scenario) and a maximum (corresponding to a situation in which water flow is reduced but total nutrient loads remain unchanged). Henceforth, we used a second water-reduction scenario (NUTS), in which water flow is reduced in the same amount as in the EXT, but total loads of nutrients to the sea are kept constant as in REF, as a sensitivity check. The impacts on the biogeochemical conditions of the Mediterranean Sea of this NUTS scenario are presented in the main text ('Impacts on the biogeochemistry section').

The marine models within Blue2MF (biogeochemical and HTL) are forced with the EXT and NUTS freshwater scenarios during the period 2008–2018 (see Fig. 1a), and ecological variables are extracted for the period 2015–2018, as in the REF simulation, to minimise any drift from the initial conditions.

Satellite-based proxy for potential fish productivity

As an independent proxy for potential fish productivity, the Ocean Productivity Available to Fish (OPFish) index[82] is used. This satellite-derived proxy, which was calibrated using numerous HTL species feeding habitats and validated against spatial fisheries data[82], identifies the local fishing opportunities by quantifying the useful fraction of plankton production that mostly supports fish catches (secondary production). This index daily integrates the presence and intensity of productivity frontal features (surface chlorophyll-a horizontal gradients), which stand long enough to sustain zooplankton production[83,84], while removing the potential effects of eutrophication (maximum chlorophyll-a threshold).

The OPFish values integrated for the Adriatic Sea (red squares in Supplementary Information Fig. 7) show a high correlation with the Po river flow ($R = 0.81$, $p < 0.01$) for the 2003–2022 annual time series. This agrees with previous knowledge on the functioning of this ecosystem, especially on the western Adriatic Sea, which is mostly influenced by the Po River (Supplementary Information Fig. 10), further supporting the use of OPFish as a proxy for potential fish productivity.

Data availability

The datasets generated during and/or analysed during the current study are available at *figshare* with the identifier (https://doi.org/10.6084/m9.figshare.26840299) and from the corresponding author on reasonable request.

Code availability

The numerical codes for the models used in the current study are available from the corresponding author.

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Author contributions
D.M. conceived the presented idea. B.B. and I.T. developed the freshwater flow modelling; B.G., A.P., A.U. and O.V. developed the freshwater nutrients modelling. E.G.G. run the hydrodynamic-biogeochemical simulations. C.P. and N.S. run the high trophic level model simulations. J.N.D. provided the OPIFish data. J.G. provided the economic cost estimations. D.M. organised the information and drafted the paper and figures. C.C.-M., O.D., S.M., L.P. and A.S. discussed the results. All authors contributed to the final drafting of the manuscript.

Competing interests
The authors declare no competing interests.

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