Joint Research Centre

Freshwater appropriation in Europe

A preliminary assessment of current conditions, knowledge gaps and resilience prospects

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Contents

Abstract

In this contribution, we analyze the level of water appropriation in European watersheds, using available estimates of water demand and water availability to compute the ratio of demand to availability in the European Union's river basins. We highlight that demands are more uncertain than availability and deserve further research. Nevertheless, currently available estimates enable a screening level assessment. Water demand usually represents 10-50% of renewable water availability and may even exceed 100% in some regions, implying direct or indirect water reuse in the river basin, use of non-renewable water or transfers among river basins. The level of water appropriation varies significantly across Europe, generally with a North-South gradient in line with other assessments, reflecting the interplay between demand and availability. The patterns of potential appropriation depend on the water-using sectors. Irrigation systematically occurs in highly appropriated river basins and tends to be the main driver of water appropriation. Most central European regions show relatively uniform mixes of water demand, but energy or irrigation may become dominant in northern or southern regions, respectively. Climate change will exacerbate the current situation particularly for irrigation and livestock. There is a widespread potential for reuse of water across sectors, which may contribute substantially to water resilience.

Acknowledgements

This report documents a stocktaking and screening exercise conducted at the onset of work in support to the EU Water Resilience Strategy. It focuses on water demand in the context of long-standing water resources assessment activities at the JRC.

We would like to thank JRC colleague Alois Tilloy for sharing updated estimates of water demand in the EFAS setup of LISFLOOD. We also thank former JRC colleagues Hylke Beck and Emiliano Gelati for their contribution to producing and testing the initial version of the Budyko model used in the analyses presented here. Emiliano prepared the graphs shown in figures 4 and 5 in this report.

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Executive summary

Policy context

Water resilience is for a significant part about water demand management. Still, current knowledge on water demand at the European scale is not as robust and accurate as it could be, considering that water use is well known at the local and regional scale. Understanding where water is used by whom, how high the competition is for resources, and how this can be positively managed, are all critical pieces of knowledge in the implementation of the European Water Resilience Strategy (2025). This report draws a picture of water appropriation across Europe, contributing to our understanding of the challenges ahead.

Compared to previous assessments, mostly focused on consumptive water use, this report underscores the scale of human appropriation in Europe and the importance of reducing abstractions, through water reuse and water use efficiency, to secure water resilience in the European economy and society.

Key conclusions

The available data enable a first estimation of water demand in Europe, but this is affected by significant uncertainties, overriding uncertainties in the estimation of water availability. Energy appears as the main responsible for water abstraction, followed by agriculture (irrigation), but most European regions do not feature a dominance of one sector over the others. Energy and irrigation are the “game makers” of water appropriation where they are present, while in many river basins they play a less prominent role. Public water supply is often a significant “player” but not a “game maker”, while livestock is usually a “game taker”. The picture on industrial water use is more complex, arguably less well captured by existing estimates, and quite possibly under transformation as a consequence of emerging sectors under development (e.g. semiconductors or energy storage).

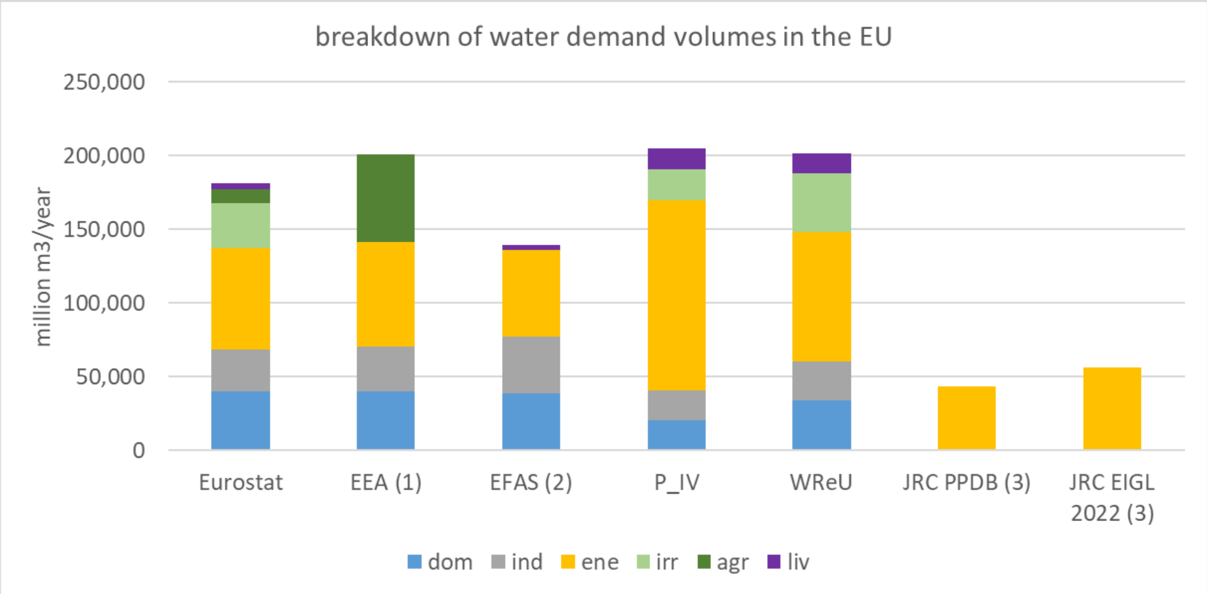
There is widespread potential for water reuse not only of domestic wastewater for irrigation, but also across other sectors. Reusing water and improving use efficiency in all sectors is key to reduce water appropriation.

Future work will be required in order to improve our understanding of water demand, particularly in the agriculture, industry and energy sectors, towards building accurate European water balances enabling support to water resilience policies.

Main findings

Our knowledge of water demand by different sectors in Europe could be improved. As shown in Figure A1, different estimates suggest a range of demand volume between ca. 140 and 200 billion m^3/year, with a certain variability also in the breakdown among sectors. However, energy is always identified as the main sector when it comes to abstractions, followed by irrigation. Concerning the latter, data gaps may be very significant. For example, the EUROSTAT data after year 2000 do not contain reported irrigation abstractions for the second largest EU irrigation water user (Italy), where national statistical data from the year 2010 indicate an irrigation volume in excess of 11 billion m^3, in line with the data curated by the EEA.

Figure A1. Comparison of demands from different sources



Notes: (1) Livestock not included. (2) Irrigation not included. (3) Only energy.

Source: JRC

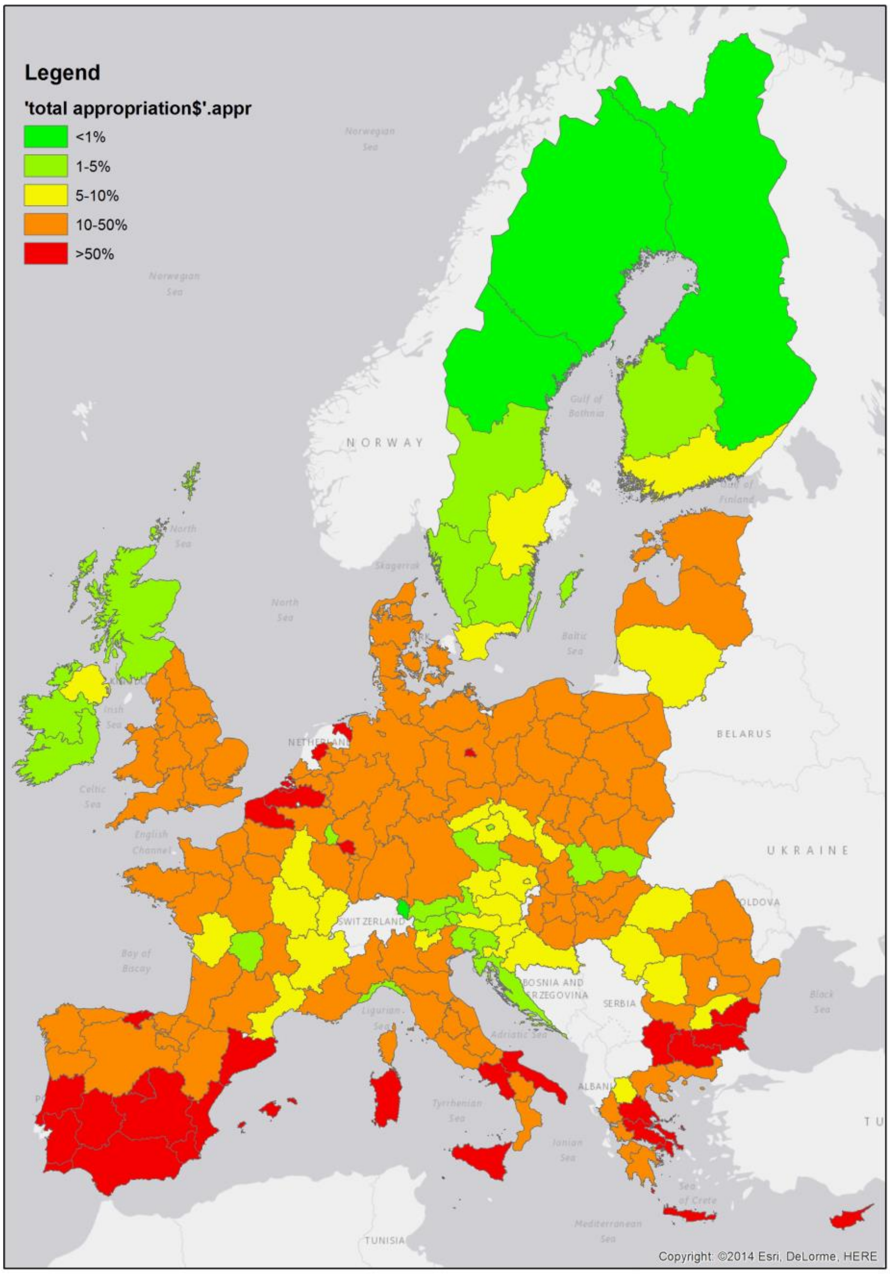
An estimated appropriation of naturally available resources is shown in Figure A2. It appears that human activities abstract between 10 and 50% of naturally available volumes, and in some cases (particularly in the South of the EU) even more than 50%. Only a part of this abstracted water is eventually returned to the environment, with altered timing and/or quality, potentially causing stress to water ecosystems and competition among water-using sectors.

The sectors contributing the most to the appropriation of water vary across Europe. The graph of Figure A3 shows the combined contribution of energy, public water supply, irrigation, industry and livestock to the appropriation of resources. In northern countries where climate change may cause increased water flows, we expect a slightly reduced level of appropriation on an annual basis in the future. On the contrary, the situation in the South is projected to significantly worsen.

Irrigation is already the sector taking water from the most appropriated river basins, and the situation may significantly worsen with climate change (see graph of Figure A4).

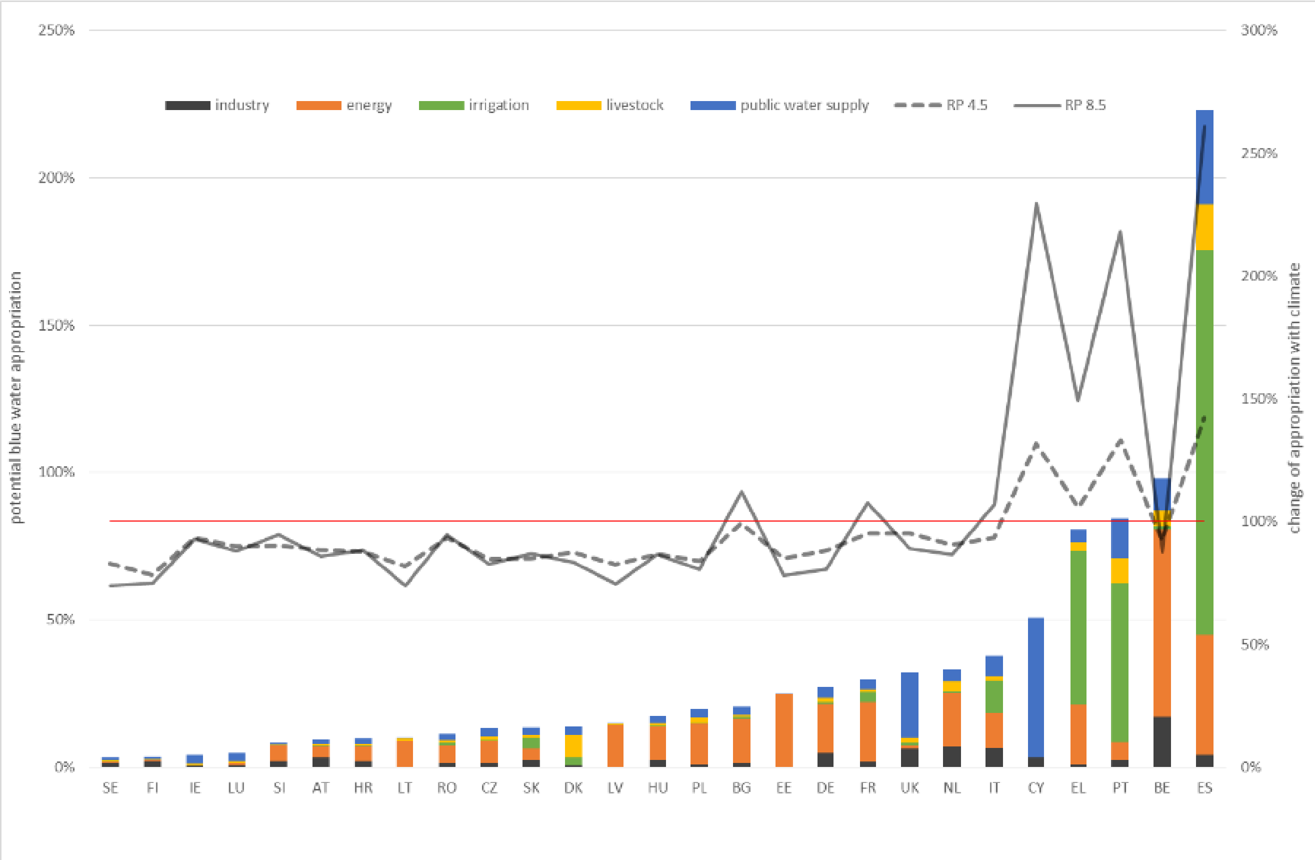
An exploration of opportunities for reuse shows a potential beyond the already well established area of wastewater reuse for irrigation, requiring more specific assessments also in order to address water quality issues.

Figure A2. Total appropriation



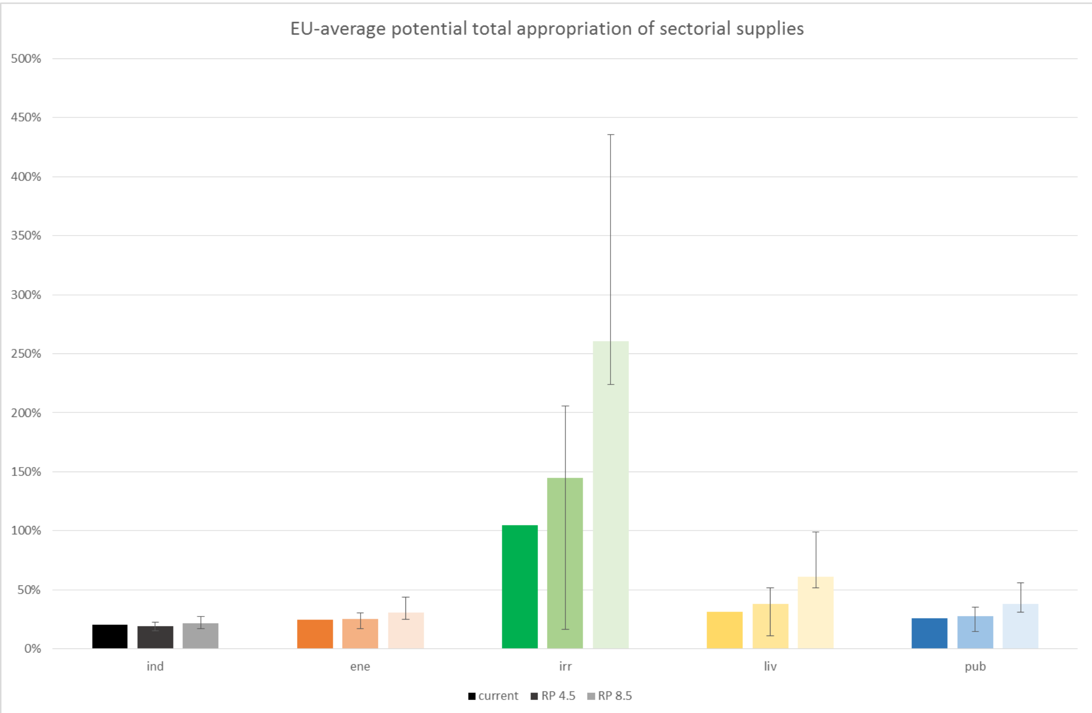
Source: JRC

Figure A3. Sectorial contributions to appropriation and changes with climate scenarios



Source: JRC

Figure A4. Sectorial water resources appropriation



Source: JRC

Related and future JRC work

A good understanding of demand and availability is the basis to build European water balances as essential tools supporting investments and management for water resilience.

While water availability is relatively well understood, it will be necessary to work on a better representation of water demand at the European scale. To this end, data already collected and made available in the EU through EUROSTAT and the EEA could be complemented with specific data products, particularly for irrigation, energy and industrial water demand.

Quick guide

- In § 2, we present an estimation of annual water availability based on the Budyko framework, which we show to be acceptably in line with observations and a good approximation of the water volume simulated with the more complex model LISFLOOD. Moreover, we compare options to estimate water abstractions or demand at the European scale. Availability and demand from the different economic sectors are the key ingredients to draw a European water balance and assess the degree of water appropriation with spatial detail across the EU.

- In § 3, we aggregate the appropriation indicator at regional scale, and we make use of it to assess how the various economic sectors contribute to water appropriation, as well as the overall level of appropriation of the water sources they rely upon. We identify where a certain sector may be a "game maker" or a "game taker" in water appropriation, and whether appropriation is concentrated in a few water bodies or widespread on the stream network.

- In § 4, we systematically examine the possibilities of water reuse across economic sectors in Europe, by analyzing the relative position of users in a river basin. When activities in a sector tend to happen downstream of activities in another sector, and when the volumes used in the upstream sector are significant compared to those in the downstream sector, there can be a favorable condition for water reuse. This circumstance is occurring in Europe particularly for reuse of domestic water in irrigation.

- In § 5, we further explore how domestic water reuse for irrigation can contribute to reducing water appropriation, and we examine how opportunities for this reuse vary across the EU, taking into account additional criteria.

- Finally, § 6 proposes a perspective towards improved mapping of water appropriation and the water balance in the EU, as a ground for designing cost-effective management measures under the EU Water Resilience Strategy.

1 Introduction

Human activities compete for the use of water among themselves and with environmental flow requirements. The EU Water Resilience Strategy (WRS; EC, 2025) aims to help the European Union (EU) improve water management towards a fair balance between water supply and water demand responding to current needs. Among various actions foreseen in the strategy, the Commission committed to promoting the exchange of best practices on water balances across all economic sectors. Understanding the water balance is essential in order to design measures towards water resilience, and understanding the uncertainty affecting the EU water balance is key to focus future water intelligence work.

This report has three objectives:

(1) Compare quantifications of the volumes of water demand from key economic sectors, and volumes of water available from the natural water cycle, to understand the current uncertainties affecting the estimates;

(2) Assess indicators of human water appropriation at the European scale under current and future climatic scenarios affecting water availability. As an approximation for more detailed water balances compiled at the river basin or local scale, the indicators highlight the river basins most under stress, how competition for water and stress in aquatic ecosystems may exacerbate in the future, the sectors contributing the most to appropriation and their potential competition.

(3) Through the lens of the appropriation indicators, explore how reuse can help reduce competition for water and the associated stress in water systems[1].

By *appropriation* we refer to water subtracted from its natural flow even if eventually returned to the environment. While many assessments have focused on *consumptive* water use as the main cause of deterioration of the water balance in a river basin (see e.g. Nogueira Sondermann and Proença de Oliveira, 2022), we regard appropriation as a pressure indicator, because of the chemical and physical pollution loads (e.g. nutrients, higher temperature) and altered timing of flows it causes, even if water is not effectively consumed (Vanham et al., 2018). To quantify appropriation, we use the water exploitation index (WEI), i.e. the ratio of an estimated annual water abstraction volume to an estimated annual volume of water available[2]. We assume that abstractions coincide with the demands of the different sectors (i.e. neglecting unmet demand). In the European context and under historical climate, this assumption can be usually justified because, if an activity is established, supply to meet its demand is generally secured at least under ordinary conditions. This may no longer hold true under a modified climate, when droughts and water

[1] The management measures available in order to reduce water appropriation, without structural changes to the economy, include the enhancement of water use efficiency and the reuse of water across sectors. Quantifying water saving through increased use efficiency requires first a sound understanding of demands and abstractions and will be a subject of future assessments. Use of alternative water sources, such as desalination, while obviously contributing to reducing freshwater appropriation, entails aspects that are more complex. This will not be elaborated any further in this report.

[2] When the WEI is computed using the net abstraction instead of the total abstraction (i.e. by subtracting to the numerator the returns of water to the stream network from the various activities), it is sometimes referred to as the "WEI+", e.g. by the EEA (https://www.eea.europa.eu/en/analysis/indicators/use-of-freshwater-resources-in-europe-1?activeAccordion=ecdb3bcf-bbe9-4978-b5cf-0b136399d9f8). We will not consider the latter in this work.

scarcity may become more frequent, causing activities to scale down because of lack of water. While human activities can compete also on “green water”, i.e. water in soils and vegetation, in this assessment we focus on the so-called “blue water”, i.e. precipitation in excess of evapotranspiration that can be found in water bodies such as aquifers, rivers and lakes

The level of water appropriation represented by the indicator is a condition of each river basin reflecting the balance between the water volumes available, and the abstractions occurring in the watershed. In our indicator we do not distinguish between abstractions from surface and from groundwater, under the assumption that surface water and groundwater catchment areas coincide[3]. While surface water abstractions may have an immediate impact on stream habitat, groundwater abstractions impinge on resources that should eventually contribute to river recharge, but the effect on stream ecosystems can be substantially delayed. Moreover, they may cause different types of impact, including land subsidence due to aquifer compaction and the alteration of exchanges between aquifers and rivers. Our indicator is designed to reflect the combination of groundwater and surface water abstraction, without specifically emphasizing any of the two.

This report is organized as follows:

- In § 2, we present an estimation of annual water availability based on the Budyko framework, which we show to be acceptably in line with observations and a good approximation of the water volume simulated with the more complex model LISFLOOD. Moreover, we compare the available options to estimate water abstractions or demand at the European scale. Availability and demand from the different economic sectors are the key ingredients to draw a European water balance and assess the degree of water appropriation with spatial detail across the EU.

- In § 3, we aggregate the appropriation indicator at regional scale, and we make use of it to assess the how the various economic sectors contribute to water appropriation, as well as the overall level of appropriation of the water sources they rely upon. We identify where a certain sector may be a “game maker” or a “game taker” in water appropriation, and whether appropriation is concentrated in a few water bodies or widespread on the stream network.

- In § 4, we systematically examine the possibilities of water reuse across economic sectors in Europe, by analyzing the relative position of users in a river basin. When activities in a sector tend to happen downstream of activities in another sector, and when the volumes used in the upstream sector are significant compared to those in the downstream sector, there can be a favorable condition for water reuse. This circumstance is particularly occurring in Europe for reuse of domestic water in irrigation.

- In § 5, we further explore how domestic water reuse for irrigation can contribute to reducing water appropriation, and we examine how opportunities for this reuse vary across the EU, taking into account additional criteria.

- Finally, § 6 proposes a perspective towards improved mapping of water appropriation and the water balance in the EU, as a ground for designing a cost-effective water resilience strategy.

[3] This is not always necessarily true in reality, but is a first approximation valid for large-scale analysis.

2 Mapping water appropriation: the European water balance

The indicator that we adopt for appropriation is the water exploitation index (WEI), i.e. a ratio of abstractions to water availability. Looking at a generic river basin, the appropriation indicator is defined as the ratio of demand to availability:

Equation 1. Appropriation index for the j-th river basin

$$\alpha_j = \frac{D_j}{Q_j},$$

where $D_j = \sum_{i=1}^{s} D_{ij}$ is the total demand of s water-using sectors considered in the river basin in the j-th river basin, D_{ij} is the cumulative demand of the i-th sector, and Q_j is the annual average availability. The calculation entails estimating demands and availability. Demands are usually estimated from reported water use statistics, suffering from data gaps and inaccuracies. Even when statistics are reliable, they are usually available in aggregated terms, often at country level, hence attribution of water use to a specific river basin entails some spatial modelling of water demand. For irrigation, crop water requirements may be estimated from weather forcing using well established modelling approaches or the methods of FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998), practically considered a global standard.

Water availability is the total volume of water that flows through a catchment because of precipitation in excess of evapotranspiration. We call this quantity the "water surplus". Although groundwater includes reserves stocked in isolated aquifers that are no longer recharged by infiltration ("fossil aquifers"), here we only focus on "renewable" groundwater, i.e. water in aquifers that are regularly recharged ("active aquifers"). In the long term, all the water in active aquifers undergoes a turnover and ends up seeping out into the stream network. Process-based hydrological models such as LISFLOOD (Burek et al., 2013a) calculate the contribution of groundwater to streamflow explicitly. Moreover, such models allow a description of the variability in time of streamflow. However, as we are interested in the total annual surplus (combining together surface and groundwater), a simpler model can be as fit-for-purpose. In particular, the Budyko framework (Budyko, 1974) has proven to be a practical choice. This framework provides a simple and computationally inexpensive way to calculate an annual average water surplus from a climatology of precipitation and potential evapotranspiration.

In order to deliver a proof of concept, here we calculate the water appropriation indicator using a Budyko-based estimate of surplus and an estimate of water demand readily available from previous studies. A comparison of these estimates with available alternatives highlights their robustness for the purposes of the present study.

2.1 Spatial resolution of the analysis

The indicator of **Equation 1** can be calculated for any river basin, i.e. for any location on the stream network, by summing the demands occurring in the contributing area upstream, and dividing them by the water availability at the same location, equal to the streamflow under natural conditions (i.e. gross of any abstractions actually occurring). As any measurement of streamflow would reflect such actually occurring abstractions, and simultaneous measurements of abstractions are practically inaccessible, water availability is usually estimated with a model. Besides confounding water demands with abstractions, we are also implicitly assuming that abstractions occur at the spatial location of demand, while in reality demands may be met with water supply from distant sources. For both reasons, the indicator must be interpreted as "potential" water appropriation.

In this contribution we represent continental Europe with a resolution of 1 km^2. We use the GTOPO30 digital elevation model (DEM)[4], following a projection to a grid of 1 km resolution in Lambert Azimuthal Equal Area (LAEA) coordinates, after burning in the stream network of the HydroEurope dataset (Bouraoui et al., 2011). The resulting DEM is then processed to remove pits and calculate flow directions using the standard functionalities of ESRI's ArcGIS 10.7 Spatial Analyst ©. These flow directions enabled application of hydrological operators, including weighted flow accumulation and flow length, as explained in the following. All input data used for the calculations were resampled to the same 1 km grid resolution. For the calculation of catchment level indicators we extracted all the grid cells with a contributing area of 500 km^2 or a multiple of 500 km^2. Overall, we consider ca. 4300 catchment outlets as points. These were converted into points representing the corresponding catchment outlets, at which we extracted all parameters needed for the calculations. Aggregation of any parameter over the j^{th} catchment is computed as the weighted flow accumulation of the spatial distribution of the parameter, using the flow direction map obtained as above. For example, demand in the j^{th} catchment is computed as:

Equation 2. Cumulative demand to assess water appropriation

$$D_j = \sum_{i=1}^{s} D_{ij} = \sum_{i=1}^{s} \int_{(x,y)\in A_j} \delta_i(x,y)\, dxdy$$

A_j being the catchment area of the j-th river basin, and $\delta_i(x,y)$ the spatial distribution of demand from the i-th sector within the river basin.

2.2 Water availability

2.2.1 Appraisal of water availability as estimated with the Budyko model

The framework proposed by Budyko (1974) enables the estimation of long-term average surplus S=P-ET, where ET is long-term average annual evapotranspiration, and P is long-term average annual precipitation, based on a simple relationship with the climate of a catchment. The literature offers several variants of an equation to represent this relationship. In this assessment, we refer to the variant proposed by Zhang et al., 2001:

[4] Global 30 Arc-Second Elevation (GTOPO30) Digital Object Identifier (DOI) number: /10.5066/F7DF6PQS

Equation 3. Calculation of surplus using the Zhang et al., 2001, formulation of the Budyko model

$$S = P\left(1 - \frac{P + wE_0}{1 + w\frac{E_0}{P} + \frac{P}{E_0}}\right)$$

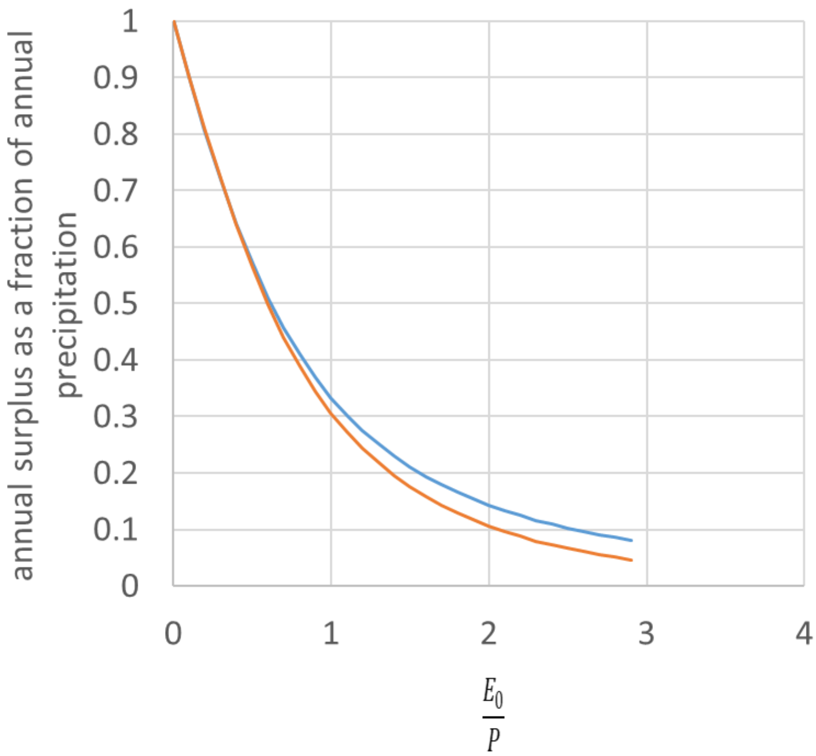
Where E_0 is potential evapotranspiration and *w* is a parameter termed the plant-available water coefficient (Zhang et al., 2001) representing the relative difference in the way plants use soil water for transpiration. The term $\frac{E_0}{P}$, sometimes called the "aridity index", depends only on the climate of a region, while *w* may be related in principle to vegetation and land cover. In this assessment we assume *w*=1, yielding a "midway" estimation reasonably representative of average European conditions. Assuming *w*=1 makes the model very close to the original, non-parametric equation proposed by Budyko:

Equation 4. Calculation of surplus using the original Budyko (1974) model

$$S = P\left(1 - \sqrt{\left(1 - e^{-\frac{E_0}{P}}\right)\frac{E_0}{P}\tanh\left(\frac{P}{E_0}\right)}\right)$$

A comparison of the two formulations highlights a sizable discrepancy only in arid climates, with high $\frac{E_0}{P}$ (**Figure 1**).

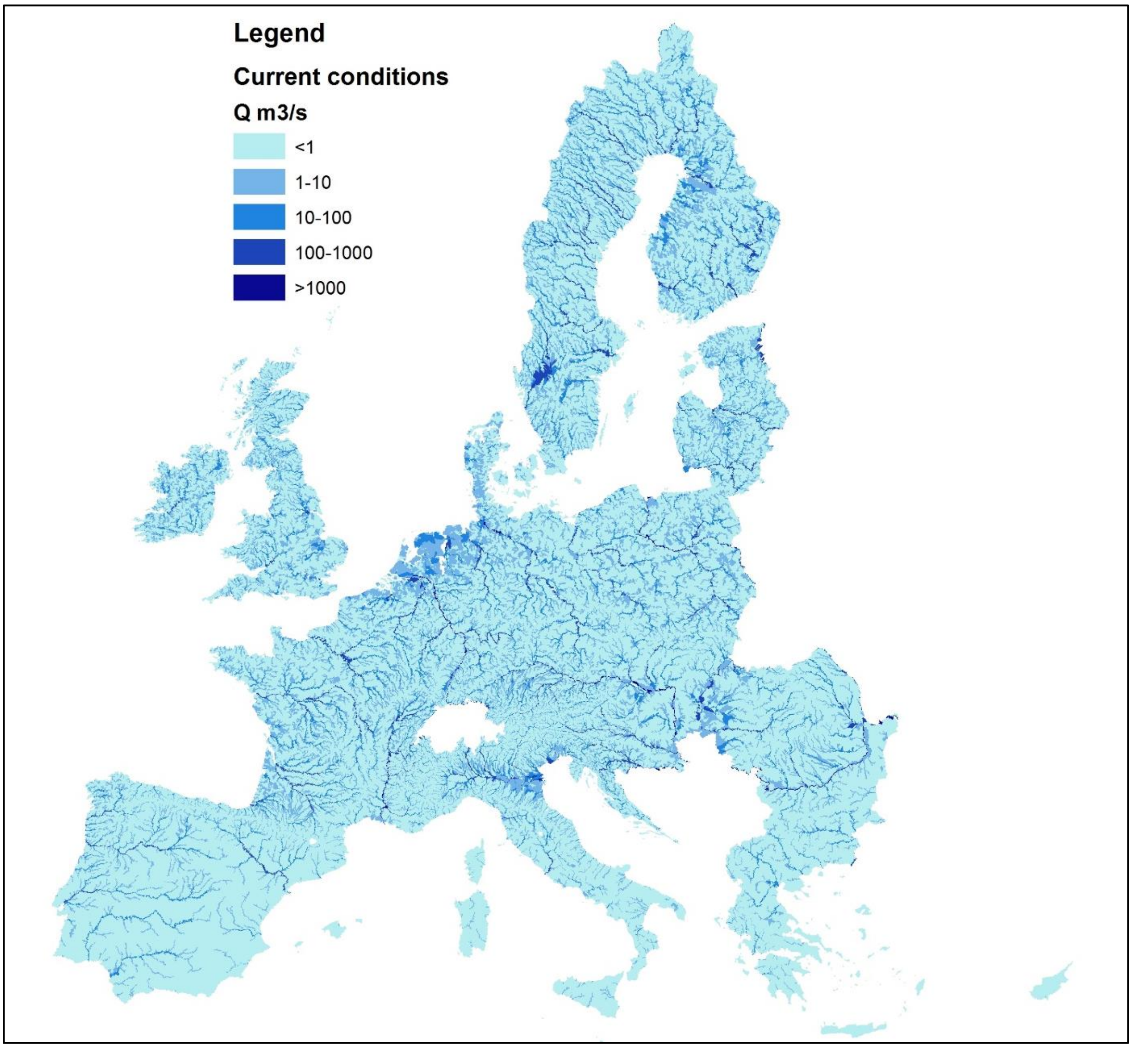
Figure 1. Comparison of surplus from **Equation 3** (blue line) and **Equation 4** (orange).



Source: JRC

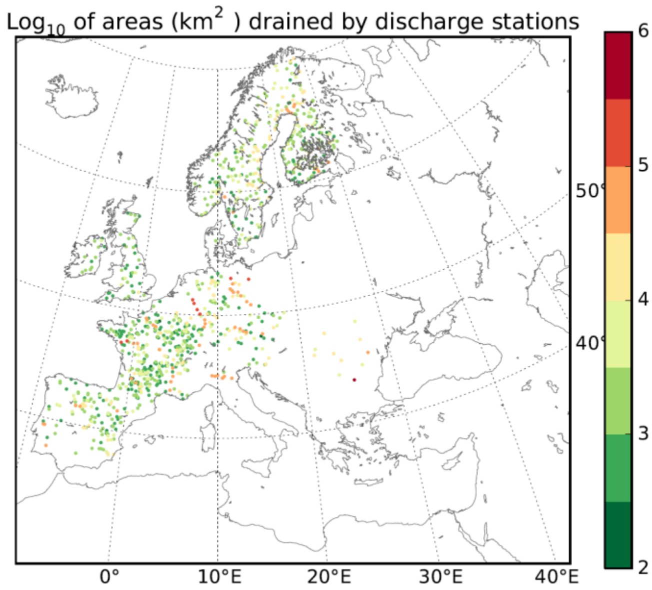
In this study we make use of the calculation adopted in previous JRC studies including Pistocchi et al., 2015, Pistocchi et al., 2019 and Pistocchi et al., 2022. In this analysis, we assume the average of E_0 and P over the period 1990-2010 to represent current conditions. Using the weather forcing time series from Ntegeka et al., 2013, and computing E_0 with the Penman-Monteith model using the LISVAP code (Burek et al., 2013b), we calculated annual average precipitation and potential evapotranspiration, hence water surplus. This was accumulated along the stream network to obtain the annual average discharge Q for all the sub-basins considered in this study (Figure 2).

Figure 2. Annual average discharge Q (m^3/s) in the European stream network, resulting from the long term average surplus with **Equation 3**.



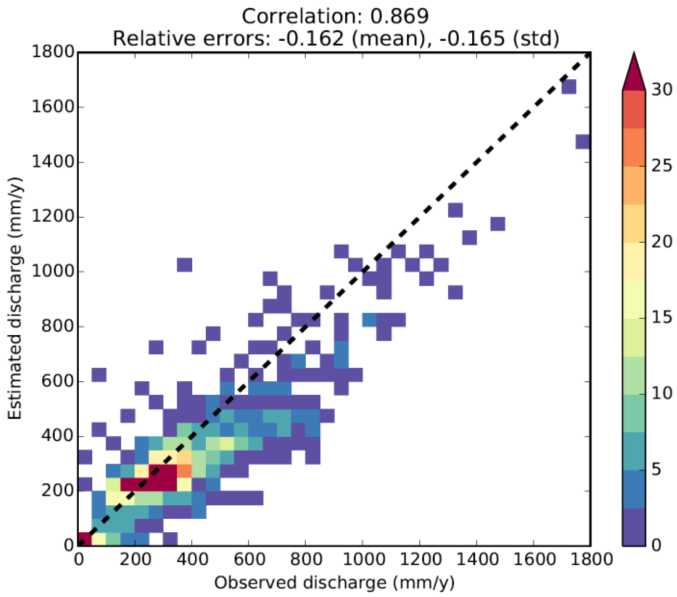
Source: JRC

Figure 3. Distribution of the stations used for model validation.



Source: JRC

Figure 4. Two-dimensional histogram of observed vs Budyko model-estimated discharge per unit area. The color bar represents the number of stations in each bin.



Source: JRC

The Budyko model predictions of Q divided by catchment area (average catchment surplus) have been compared with long term average discharge per unit area as measured at a set of European stations spanning a range of catchment areas from hundreds to almost 1 million square km (Figure 3) from the European Flood Awareness System (EFAS) as of 2015. A station was used for validation if (1) it is not in a headwater catchment; (2) the average river discharge does not exceed the average precipitation; (3) it has at least 50% daily observation rate for at least 50% of the months for each year; and (4) 50% of the years for each month. Criteria (1) and (2) have been applied in order to reduce the errors due to precipitation measurement uncertainties, while (3) and (4) to reduce biases deriving from a non-homogeneous time distribution of the discharge measurements (e.g. observations systematically missing in winter, or missing more at the end than at the beginning of the period). The last considered year was 2005.

The model has been found capable of reproducing unit discharges to a satisfactory extent (see Figure 4), although with a slight negative bias (about 16%). This indicates that runoff may be slightly underestimated, but is generally well predicted over Europe.

2.2.2 Additional tests on the Budyko model for water availability

For the sake of an additional test, we compared a Budyko model calculation according to **Equation 3**, with the annual average discharge calculated using the LISFLOOD model (Burek et al., 2013a) under the EFAS v.5.0 setup[5], and with annual average discharge measured at a number of additional stations meanwhile available for the calibration of the EFAS setup of LISFLOOD. In addition to the LISFLOOD EFAS v.5.0 simulation, we run a simulation of streamflow assuming that there is no abstraction of water in LISFLOOD, which represents a "naturalized" streamflow. The Budyko model (**Equation 3**) was applied using as input the same annual potential evapotranspiration and annual precipitation used for the LISFLOOD simulations, covering a period from 1990 to 2010, and w=1. A comparison of the average flows during the whole period is shown in **Figure 5** and **Table 1**. The scatter plots highlight several stations with a high discrepancy and no correlation between observations and model predictions. These likely correspond to a wrong match of the station with the LISFLOOD gridcell, and may be corrected in the future. If we focus on the stations where the discrepancies do not exceed a factor 10, the three models are capable of explaining most of the variance (R^2 equal to 0.95 for the Budyko model and 0.96 for the LISFLOOD runs). The Budyko model has a higher RMSE (ca. 142 m^3/s compared to 104 and 108 for LISFLOOD naturalized flow and reference run, respectively). The slope of the best fit line, indicative of the mean discrepancy between model and observations, is 1.29 for the Budyko calculation and 1.08 to 1.10 for the LISFLOOD runs.

Table 1. Performance statistics of the annual average streamflow over the period 1990-2020 computed with the Budyko model and the EFAS v.5 setups of LISFLOOD with (reference run) and without (naturalized flow) abstractions, against observations

Metric	**Budyko (w=1)**	**Budyko (w=2)**	**Naturalized flow**	**Reference simulation**
R^2	0.95	0.96	0.96	0.96
RMSE	142.3	114.2	104.7	108.2
α [6]	1.29	1.08	1.10	1.08
Median model/obs. ratios	1.12	0.92	0.96	0.93

Source: JRC

[5] https://data.jrc.ec.europa.eu/dataset/f572c443-7466-4adf-87aa-c0847a169f23

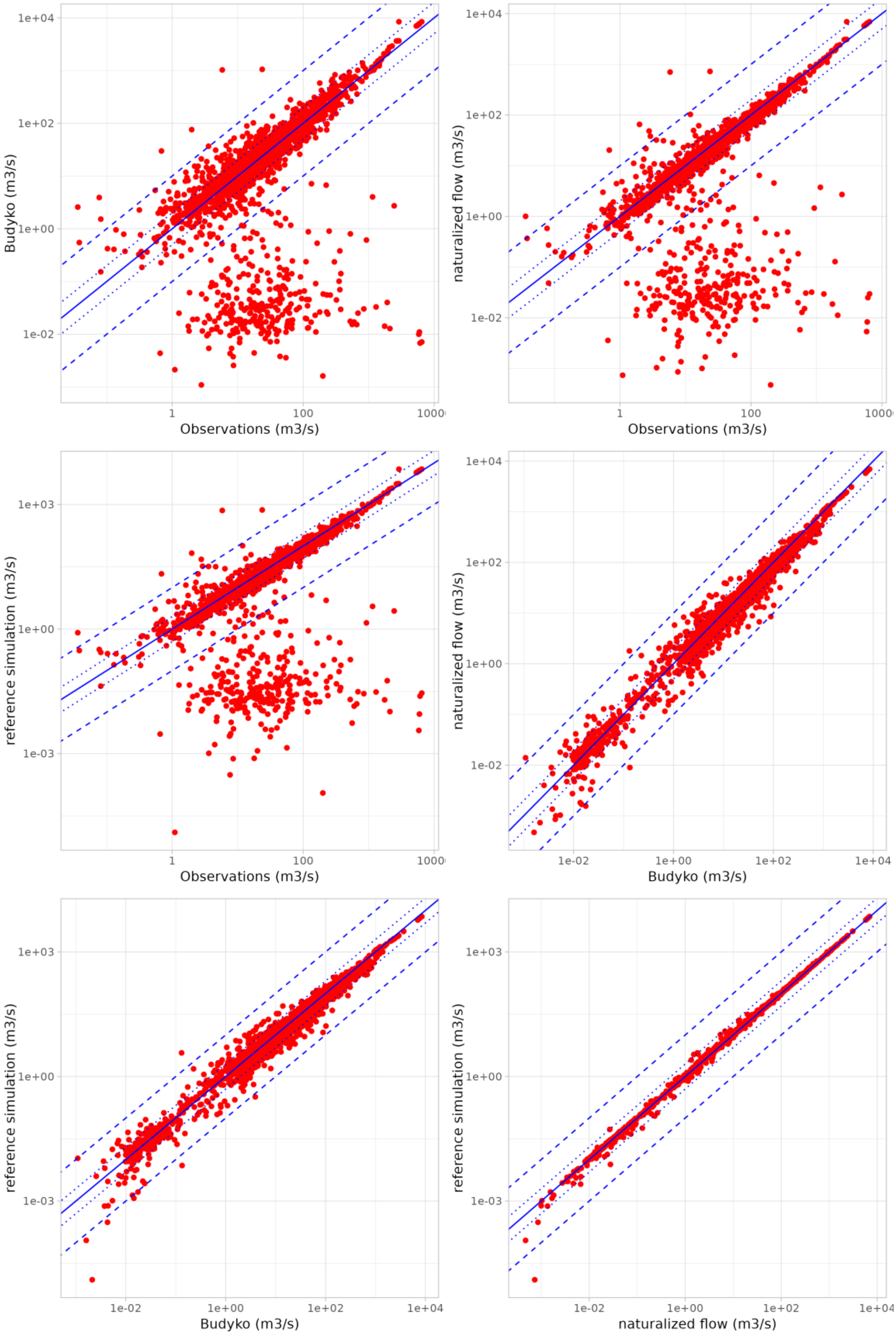
[6] slope of the best-fit line of predictions against observations, assuming zero intercept. this is the ratio of average prediction to average observation.

This setup of the Budyko model generally tends to overestimate the observations. If we inspect the histogram of the model to observation ratios (**Figure 6**), the LISFLOOD runs show a median slightly below 1 and a mean slightly above 1, while the Budyko model shows a higher bias towards overestimation. It should be noted that the Budyko model parameter, w=1, is in principle a calibration parameter and its value may affect significantly the model performance. For example, if we set *w*=2, the model calculates surplus much more in line with observations and practically very close to the reference run (**Table 1** and **Figure 6**).

The Budyko model predicts the average of surplus over several years and is not meant for the calculation of yearly surplus. However, if applied using the precipitation and potential evapotranspiration of a given year, it may provide a first approximation of the expected surplus reflecting a climate consistent with the weather of that year. For an additional check, we performed the same comparison shown above for the average of the period 1990-2020 also for the average flow of each year in that period, assuming a parameter w=2 for the Budyko model. The scatter plots present patterns similar to the ones shown in **Figure 2** (results not shown here). In **Figure 7**, we plot the values of R^2, RMSE and the slope of the best-fit line (an indicator of bias) for each year for the three models, considering only observations with discrepancies below a factor 10. In all cases, while slightly inferior, the Budyko performance is comparable to LISFLOOD in terms of annual average flow, with performance statistics in line with those of **Table 1**.

Figure 7 also shows the performance statistics of the Budyko model applied at annual steps (*w*=2), against LISFLOOD naturalized flow and reference run predictions. Both LISFLOOD simulations are apparently highly correlated, with the naturalized flow systematically higher than the reference run by approximately between 10% and 1% (slope of the zero-intercept best fit line, α, between 1.01 and 1.1). α decreases almost monotonically over time. The RMSE is always between about 5 and 10 m^3/s. The Budyko model apparently overestimates both LISFLOOD runs of about 20%, the explained variance (R^2) remains well above 90%, and the RMSE is about 50 m^3/s, with no clear time trend.

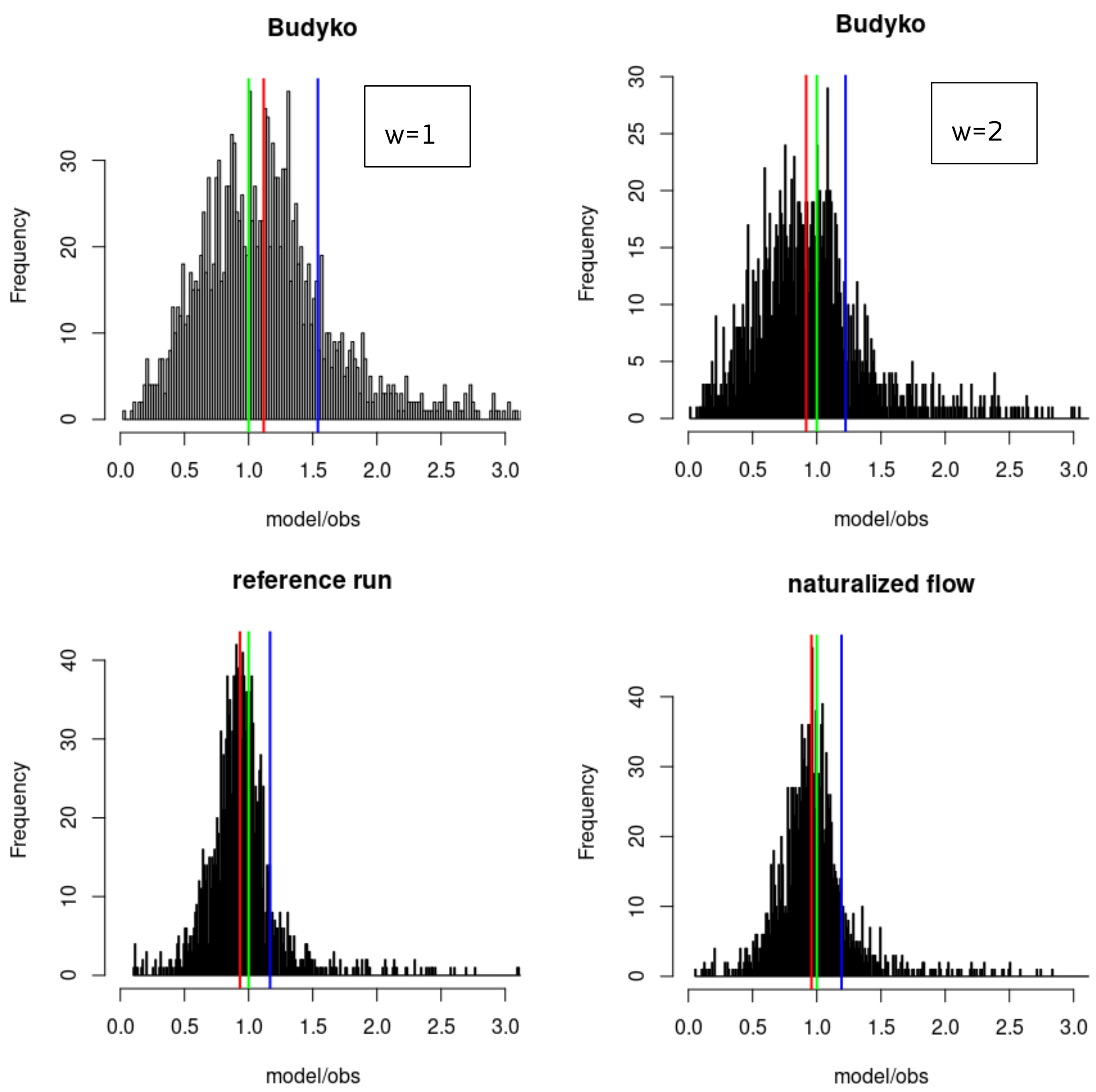
Figure 5. Scatter plots of annual average streamflow over the period 1990-2020 computed with the Budyko model (w=1) and the EFAS v.5 setups of LISFLOOD with (reference run) and without (naturalized flow) abstractions, against observations. Lines represent 1:1 match and a factor of 2 and 10 discrepancies.



Source: JRC

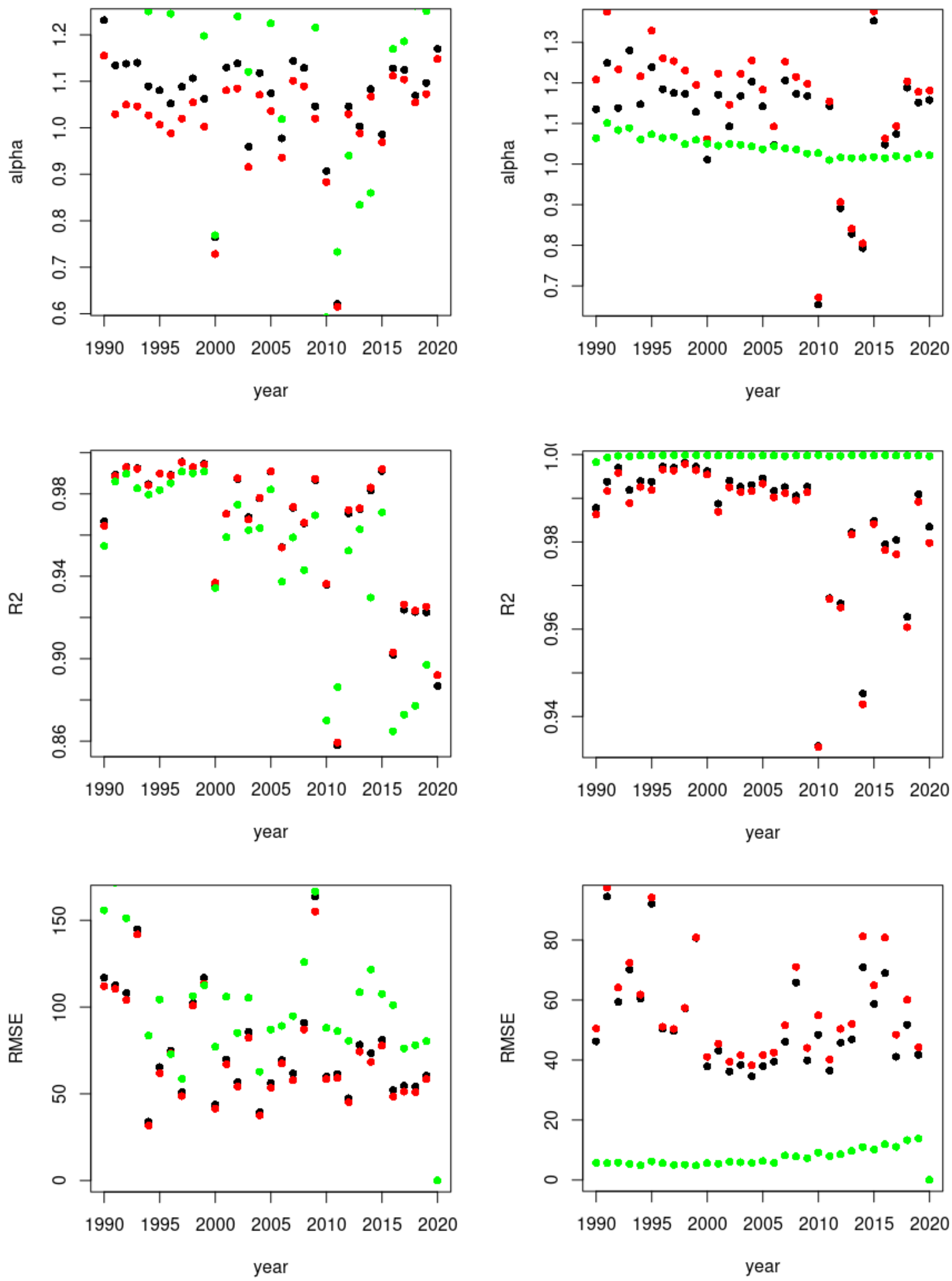
These figures support the Budyko model as a reasonable proxy of LISFLOOD runs when we focus on annual average surplus, in spite of a general tendency to overestimation (that can be minimized by calibration). As it is able to explain most of the variance of LISFLOOD model results, and being computationally inexpensive, it can be regarded as a cost-effective appraisal tool particularly when performing comparative assessments of scenarios (for example due to projected climate change).

Figure 6. Histograms of the model to observation ratio at stations with discrepancies not exceeding a factor 10. The green line is the ideal case (model equal to observation), the red line is the median and the blue line is the mean. “Reference run” and “naturalized flow” refer to the respective LISFLOOD model runs and are used as “observations” when compared with the Budyko model.



Source: JRC

Figure 7. *Left column:* Performance of the Budyko model (*w*=2: green dots) LISFLOOD naturalized flow (black) and LISFLOOD reference run (red) for every year against observed flow. *Right column:* Performance of the Budyko model against LISFLOOD naturalized flow (black dots) and LISFLOOD reference run (red). In the right column, green dots show LISFLOOD naturalized flow against reference run for every year. RMSE in m^3/s.



Source: JRC

2.2.3 Water availability under climate scenarios

The Budyko model described in § 2.2.1 was applied also with simulations of climate scenarios from an ensemble of 4 models from the EURO-CORDEX[7] experiment, under the representative concentration pathways (RCP) 4.5 and 8.5 (Moss et al., 2010) taking for E_0 and P the average over the period 2070-2100. The scenarios derive from a regional circulation model (RCM) driven by a general circulation model (GCM), run by a contributing scientific institution from the experiment. Details of the models ensemble used here are provided in **Table 2**. The models considered here are a subset of those analysed in Bisselink et al., 2020[8] and were already considered to explore climate scenarios in Pistocchi et al., 2015. The simulations allow computing the expected change in mean annual river discharge. In this assessment, we compute for the i-th level-2 NUTS region in the European Union the weighted average rate of change in river discharge under scenario *s* as:

Equation 5. Change in water availability

$$Change_{i,s} = \frac{\sum_{j=1}^{n_i}(Q_{sj}-Q_j)}{\sum_{j=1}^{n_i} Q_j}$$

Where n_i is the number of sub-basins within the i-th region, and Q_j, Q_{sj} are the current mean annual discharge and the mean annual discharge predicted under scenario s for the j-th sub-basin. In this exercise, we consider as scenarios Q_{sj} the ***median*** of model predictions for RCP 4.5 and RCP 8.5 conditions, as well as the ***minimum*** of model predictions (the "worst case" scenario). The results of these calculations are shown in **Figure 8**, indicating a clear trend of reduced availability in the south, contrasting with increasing availability in the north, with a neutral transition zone in central Europe.

Table 2. Climate models used for the assessment (GCM= general circulation model; RCM = regional climate model).

EURO-CORDEX Contributor	Driving GCM Model	RCM Model
DMI	EC-EARTH	HIRHAM5
SMHI	CNRM-CM5	RCA4
KNMI	EC-EARTH	RACMO22E
IPSL	IPSL-CM5A-MR	INERIS-WRF331F

Source: JRC

2.3 Water demand

2.3.1 Assumed demand

In this assessment, we describe total water demand in Europe as the sum of 5 sectorial water demands, namely public water demand for households, water demand for industrial production,

[7] *"EURO-CORDEX is the European branch of the international CORDEX initiative, which is a program sponsored by the World Climate Research Program (WCRP) to organize an internationally coordinated framework to produce improved regional climate change projections for all land regions world-wide."* (http://www.euro-cordex.net). Additional details on the models and access to simulation datasets can be retrieved from the above Euro-CORDEX website.

[8] https://joint-research-centre.ec.europa.eu/system/files/2020-05/pesetaiv_task_10_water_final_report.pdf

livestock breeding, irrigation and the cooling of power plants as well as large industries (chemicals, refineries, iron and steel).

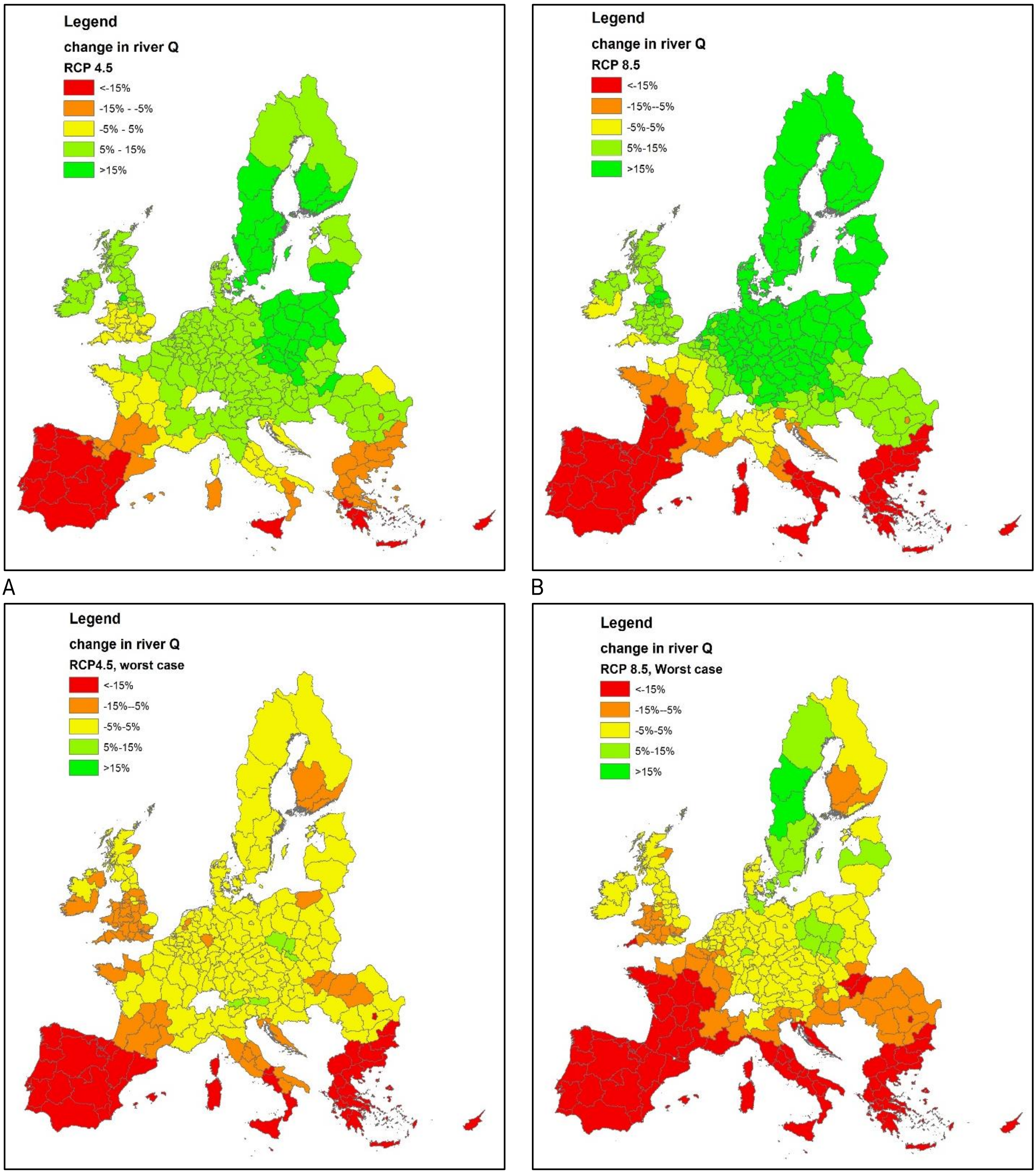
Public, industrial and energy demands are derived with the procedures described in Vandecasteele et al., 2013, and Vandecasteele et al., 2014. Livestock breeding water demand is estimated by Mubareka et al., 2013. The year of reference for water demand is 2006, and we assume that no significant change in spatial patterns and intensity of demand has occurred until present time. Irrigation water demand was estimated using the EPIC model as explained in Pistocchi et al., 2017. The original maps were resampled to 1 km resolution as input to subsequent calculations. For the sake of readability, we present the level-2 NUTS regional total demands in **Figure 9** below. This representation of demands was used in the assessment presented in Pistocchi et al., 2017, supporting the impact assessment of the Water Reuse Regulation (WReU)[9] EU/741/2020.

In order to compare demand and availability, it is necessary to consider the total demand in a river basin. The latter is divided by the streamflow volume from the river basin to obtain the appropriation indicator of **Equation 1**.

Apparently, D_j represents the cumulative upstream demand, monotonically increasing along the stream network. Its components D_{ij} are mapped below for the 5 sectors considered in the analysis (Figure 10 to Figure 12), evaluated as the flow-accumulation of demand maps. For $\delta_i(x,y)$ (Equation 2) we use the maps of demand, whose aggregated volumes are shown for level-1 NUTS regions in Figure 9.

[9] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0741&from=EN

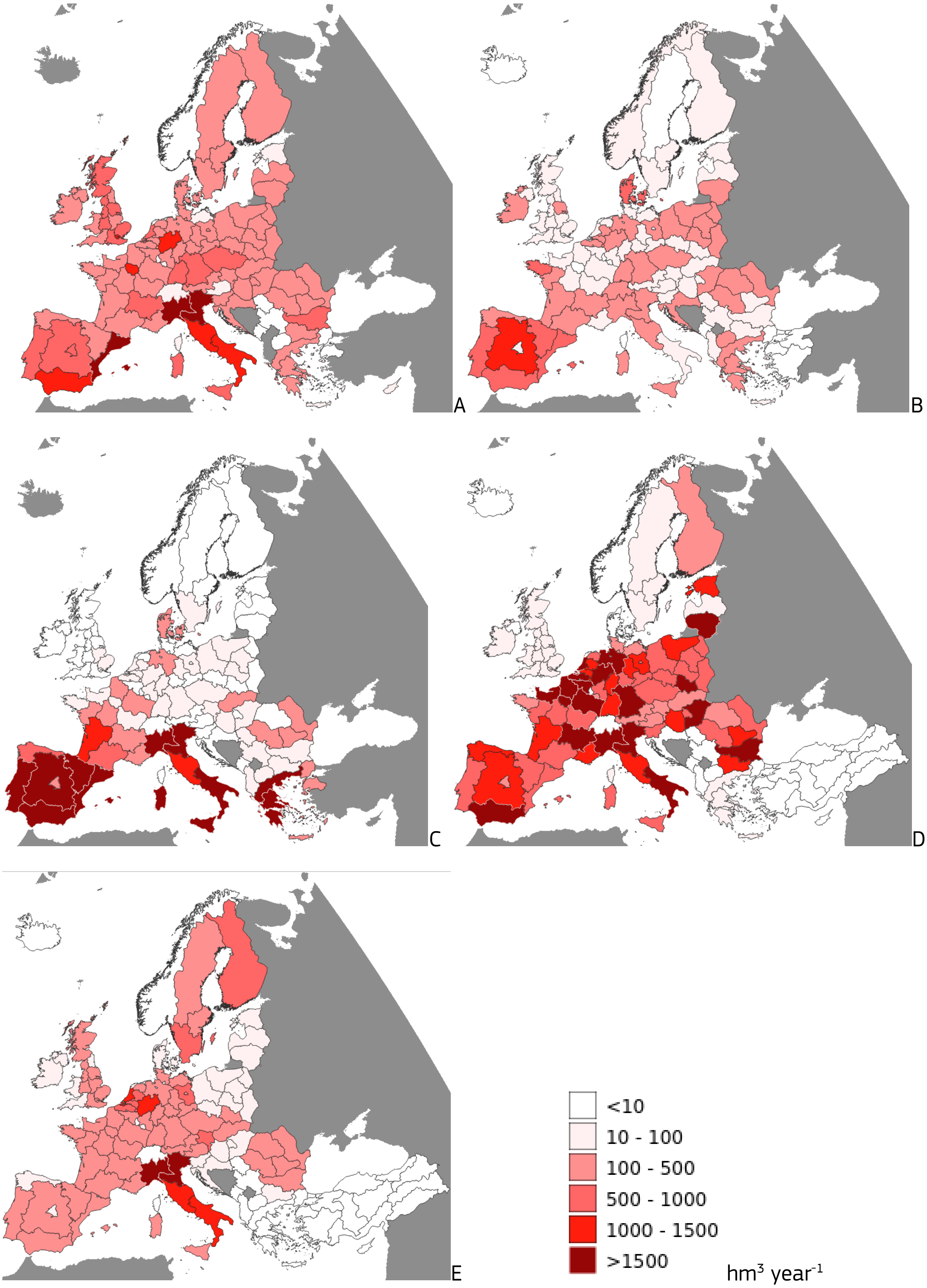
Figure 8. Change in annual average river discharge under climate change scenarios: (A) median under RCP 4.5; (B) median under RCP 8.5; (C) worst case under RCP 4.5; (D) worst case under RCP 8.5. Mean change by level-2 NUTS regions, as per Equation 5, between reference conditions (1990-2010) and climate scenarios (2070-2100).



C D

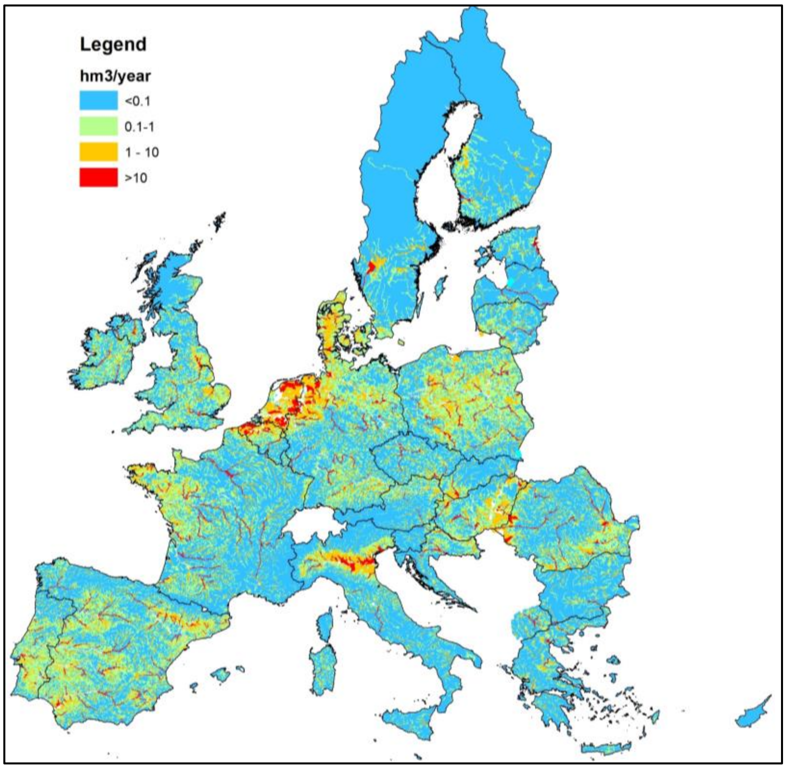
Source: JRC

Figure 9. Demand aggregated at level-1 NUTS region: (A) Domestic; (B) Livestock; (C) Irrigation; (D) Energy; (E) Industry.

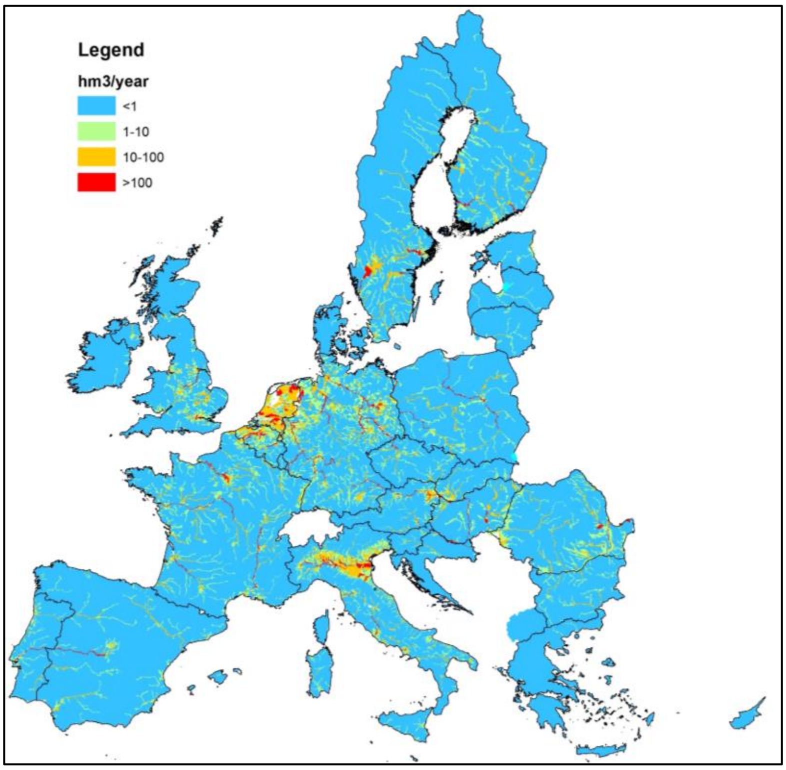


Source: JRC

Figure 10. Cumulative livestock (A) and industrial (B) water demand in European river basins.



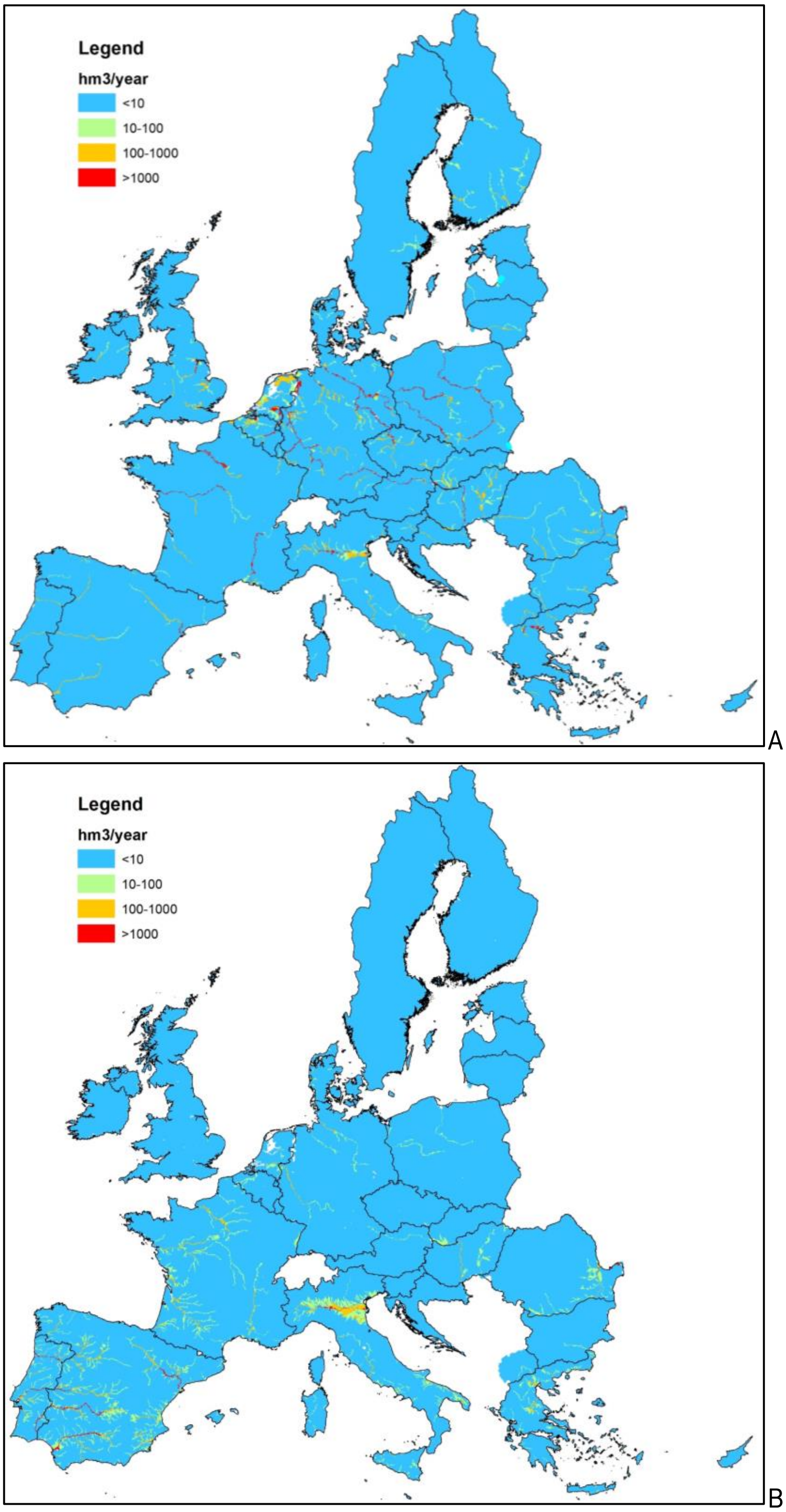
A



B

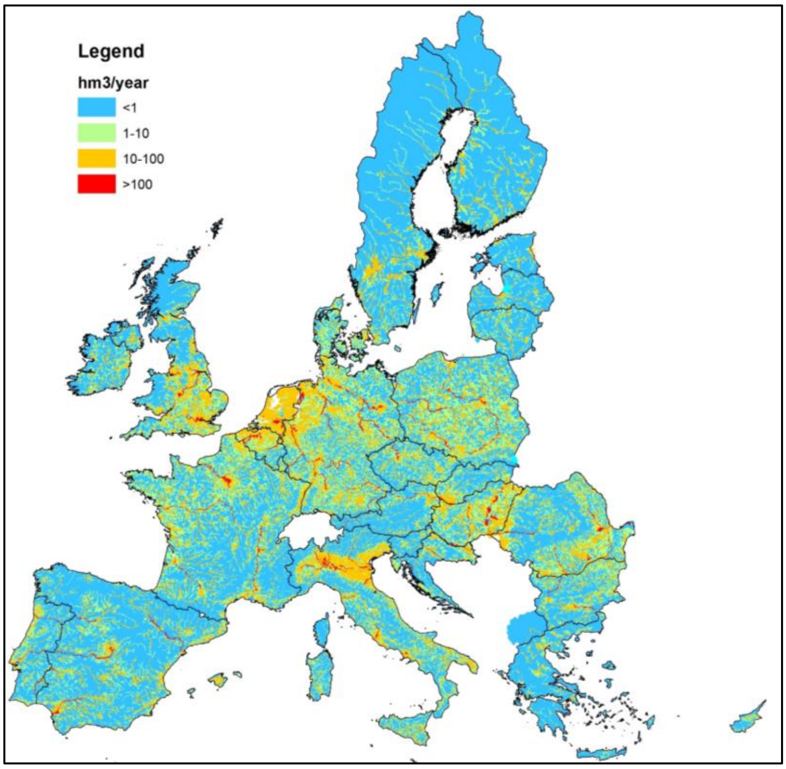
Source: JRC

Figure 11. Cumulative water demand for (A) energy (cooling) and (B) irrigation in European river basins.



Source: JRC

Figure 12. Cumulative household water demand in European river basins.



Source: JRC

In order to explore the relative importance of the 5 sectorial demands for river basins within each region in Europe, we compute Kwoka's dominance index (Kwoka, 1977) as:

Equation 6. Kwoka's dominance index

$$d = \sum_{i=1}^{n} (S_i - S_{i+1})^2$$

where n is the number of sectors (n=5) and S_i is the share of total water demand of the i-th sector. Sectors are ordered in such a way that $S_i > S_{i+1} \forall\, i$. The dominance index ranges from 0 (if all demands are equal) to 1 (if there is demand only from one sector). The dominance index for a region is computed as:

Equation 7. Kwoka's dominance index for a region with m catchments

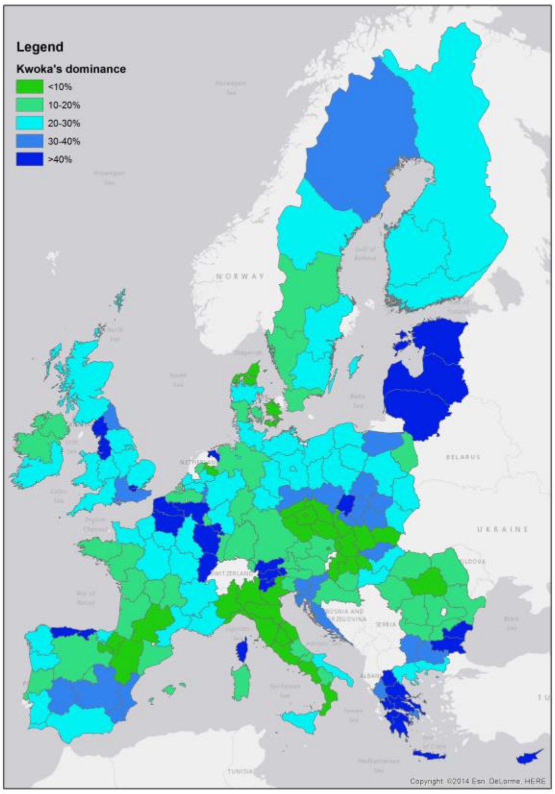
$$d_{region} = \frac{\sum_{i=j}^{m} D_j d_j}{\sum_{i=j}^{m} D_j}$$

where m is the number of catchments in the region, D_j is the aggregated demand in the j-th catchment, and d_j Kwoka's dominance index in the catchment. **Figure 13** shows the map of the index calculated as per **Equation 7**.

While demand from a single sector dominates over the others in a few regions, in most cases sectorial demands are reasonably comparable to each other.

The dominance index is quite high both in the north (where energy tends to be the main driver of appropriation) and in the south (where irrigation prevails) On the contrary, regions in northern Spain, Italy, Romania and most of central Europe do not show a dominant driver of appropriation.

Figure 13. Regional Kwoka's dominance index of sectorial demands



Source: JRC

2.3.2 Comparison with alternative demand estimates

Water abstractions data in Europe are reported from individual Member States (MS) to Eurostat[10] through the Eurostat-OECD joint survey[11]. Usually this information is available in aggregated form at national level and with a yearly time resolution. Water abstractions are separated by source (surface or groundwater) and by sector. The sectors covered by Eurostat are listed in **Table 3**. The European Environment Agency makes use of Eurostat data combined with additional data reported by the MS in the context of the Water Information System for Europe (WISE), and applies machine learning to fill data gaps. In this way, yearly data are made available[12] at the country level aggregated by economic sector according to the "*Nomenclature statistique des Activités économiques dans la Communauté Européenne*" (NACE) classification.

[10] https://doi.org/10.2908/ENV_WAT_ABS

[11] https://ec.europa.eu/eurostat/documents/1798247/6664269/Data-Collection-Manual-for-OECD_Eurostat-Questionnaire-on-Inland-Waters.pdf/f5f60d49-e88c-4e3c-bc23-c1ec26a01b2a?t=1611245054001

[12] https://www.eea.europa.eu/en/analysis/indicators/water-abstraction-by-source-and

Table 3. Water abstraction data from Eurostat and correspondence with EEA data.

Eurostat sector	Description	Correspondence with sector considered in this study	NACE sector considered by EEA
[ABS_PWS]	Water abstraction by public water supply	domestic	E36[13]
[ABS_CON]	Water abstraction by construction	domestic	F
[ABS_SER]	Water abstraction by services	domestic	E36[13]
[ABS_HH]	Water abstraction by private households	domestic	-
[ABS_AGR]	Water abstraction by agriculture, forestry, fishing	irrigation	A
[ABS_AGR_IR]	Water abstraction by agriculture, forestry, fishing - irrigation	irrigation	-
[ABS_AGR_AQ]	Water abstraction by agriculture, forestry, fishing - aquaculture	-	-
[ABS_MIN]	[ABS_MIN] Water abstraction by mining and quarrying	Industrial	B
[ABS_IND]	Water abstraction by manufacturing industry	Industrial	C
[ABS_IND_CL]	Water abstraction by manufacturing industry - cooling	Industrial	-
[ABS_ELC_CL]	Water abstraction by electricity production - cooling	energy	D

Source: JRC

Data from Eurostat and the EEA are compared with the demand estimates for sectors “domestic”, “irrigation”, “industrial” and “energy” discussed in the previous paragraph, based on the correspondences shown in **Table 3**. In addition to the data provided by Eurostat and EEA, we considered the water demand representation adopted in LISFLOOD model setups recently employed for assessments in Europe, namely the PESETA IV project[14] and the European Flood Awareness System (EFAS). The current EFAS v.5 setup of the LISFLOOD model[15] represents water demands following the approach outlined in Choulga et al., 2024. Here we compare these estimates of water demand with those of the EEA and Eurostat.

For what concerns irrigation water demand, Eurostat provides both total demand from the agriculture and food sector, and demand for irrigation alone (as well as for aquaculture), while the EEA provides only aggregated demand for the agricultural (NACE A) sector. The LISFLOOD model estimates crop water requirements dynamically based on the weather forcing. For the PESETA IV project assessment, we extracted the irrigation water demand from the model simulations as described in Bisselink et al., 2020. For the EFAS v.5 setup, calculated irrigation demand is not included in the standard model output and could not be retrieved for this analysis.

[13] NACE sectors G to U, accounting for services, are aggregated with public water supply in the EEA dataset.

[14] https://joint-research-centre.ec.europa.eu/scientific-activities-z/peseta-climate-change-projects/jrc-peseta-iv_en

[15] https://data.jrc.ec.europa.eu/dataset/f572c443-7466-4adf-87aa-c0847a169f23

For what concerns livestock, Eurostat and the EEA do not provide data. However, Eurostat provides data on livestock in Europe[16], which have been used to compute an *indicative livestock water demand*. Particularly, we assumed a demand of 130, 45, 13, 8 and 0.23 liters per head of livestock and day for milking cows, cattle, sheep and goat, pig and poultry, respectively, based on the range of values compiled in Lovelace, 2009.

Another source of information for energy water abstractions of power plants is the JRC power plant database (PPDB)[17], containing estimates of water abstractions and water consumption for the cooling of large European power plants, whose energy production is recorded in the ENTSO-E database. Water use and consumption are estimated on the basis of fixed coefficients accounting for the generation technology. In this section, we compare all the available estimates for each sector considered in this analysis. Water use for energy production is the subject of active JRC research in the context of the development of the EU Energy Atlas of the Energy and Industry Geography Lab[18]. In addition to the previously published JRC PPDB data, here we include energy water demand according to a recent update of JRC estimates (described in more detail in Annex 4 of this report), bringing it closer in line with other estimates.

We plot comparisons for domestic water demand in **Figure 14**. Data from Eurostat and the EEA data are rather consistent with each other, with minor discrepancies due to gap filling. The EEA dataset does not include abstractions from private households. The demand considered here, as well the demand in LISFLOOD setups of PESETA IV and EFAS, are within a factor 2 of the Eurostat and EEA reported demand in most cases, with a few larger discrepancies always within one order of magnitude.

For the case of industrial water demand (**Figure 15**), the estimates compare in a way quite similar to the case of domestic demand, in spite of the EEA dataset not considering water for cooling of manufacturing processes. The demand estimates used in this report seem to match better both the Eurostat and EEA reports compared to the EFAS and PESETA IV estimates. EFAS and PESETA IV seem to match each other less than they do with EEA and Eurostat data individually.

The representation of energy water demand is quite consistent across all datasets (**Figure 16**). The demand in the PESETA IV project LISFLOOD setup is systematically higher than the other representations. While in principle quite detailed, the JRC PPDB suffers from data gaps and does not cover all plants existing in Europe, which makes it prone to underestimation. Nevertheless, the correspondence with other sources of data is fair, with most countries showing water use within a factor 2 of EEA reported water abstractions, and with notable underestimation (by a factor >10) for Sweden, Lithuania, Denmark and Serbia. On the contrary, Switzerland is overestimated by a factor >10 in the JRC dataset.

For irrigation and livestock demand (**Figure 17**), the match among estimates is quite good with the partial exception of the EFAS LISFLOOD setup, which seems to underestimate significantly the requirements of livestock. Moreover, the EEA dataset does not distinguish between irrigation, aquaculture and other agricultural (NACE sector A) abstractions. In countries where irrigation

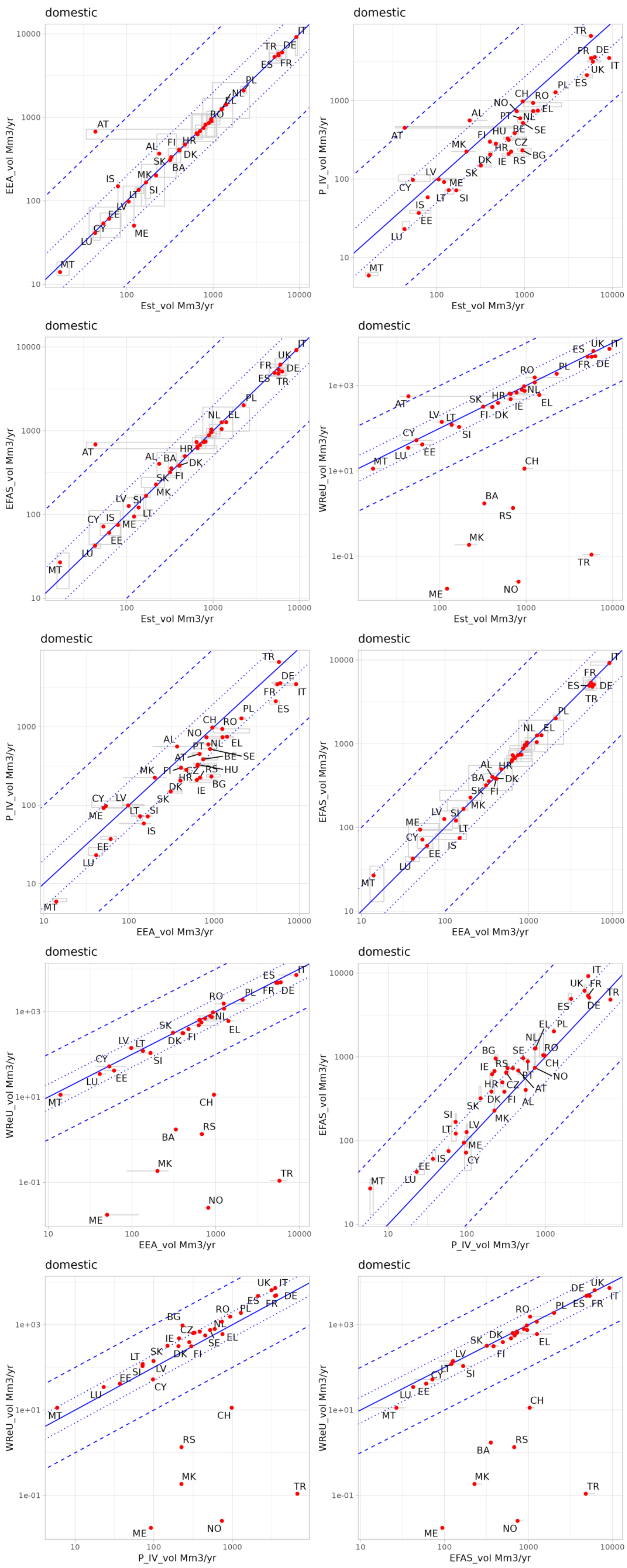
[16] https://doi.org/10.2908/AGR_R_ANIMAL, https://doi.org/10.2908/APRO_EC_POULA

[17] http://data.europa.eu/89h/9810feeb-f062-49cd-8e76-8d8cfd488a05

[18] https://joint-research-centre.ec.europa.eu/scientific-tools-databases/energy-and-industry-geography-lab_en

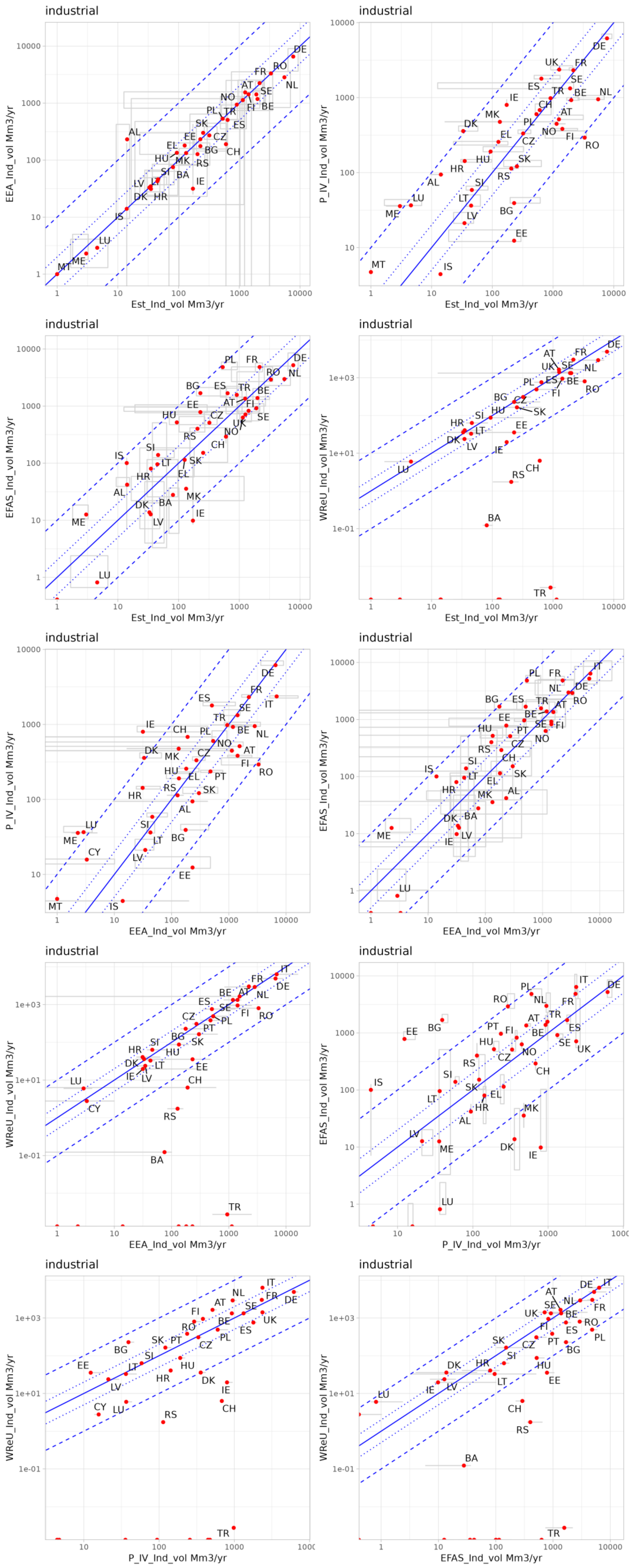
requirements are expected to be low, e.g. the Baltic states or Ireland, agricultural water requirements reported by the EEA do not seem to be a good proxy of irrigation requirements.

Figure 14. Comparisons among domestic water use reported by Eurostat (Est) and the EEA, domestic water demand from the Water Reuse study considered so far in this report (WReU), and domestic water demand in the PESETA IV project (P_IV) and EFAS. The dots represent the median of the time series for each country in the two datasets, while the boxes represent the respective ranges. Lines are factors 2 and 10 discrepancies.



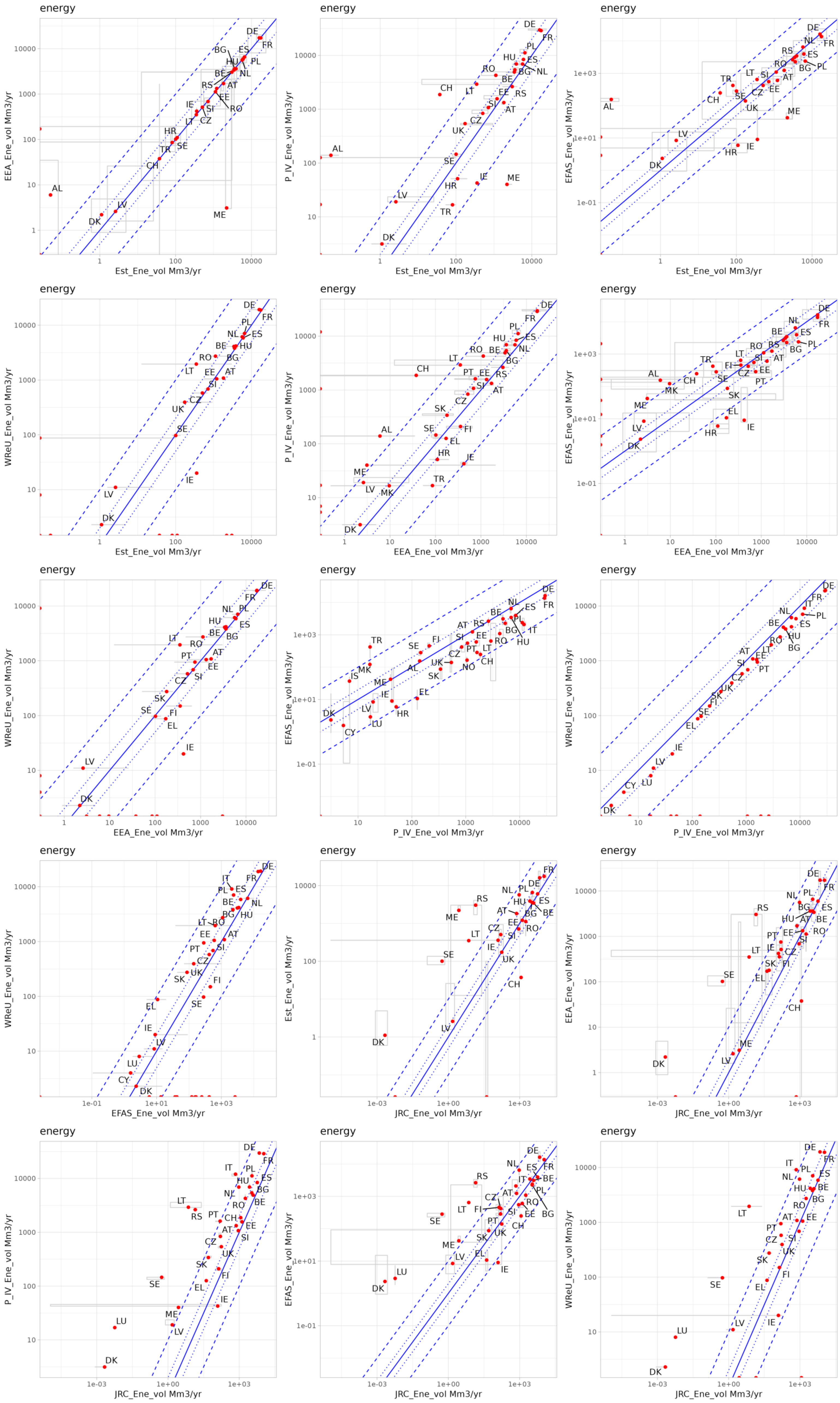
Source: JRC

Figure 15. Comparisons among industrial water use reported by Eurostat (Est) and the EEA, industrial water demand from the Water Reuse study considered so far in this report (WReU), and industrial water demand in the PESETA IV project (P_IV) and EFAS. The dots represent the median of the time series for each country in the two datasets, while the boxes represent the respective ranges. Lines are factors 2 and 10 discrepancies.



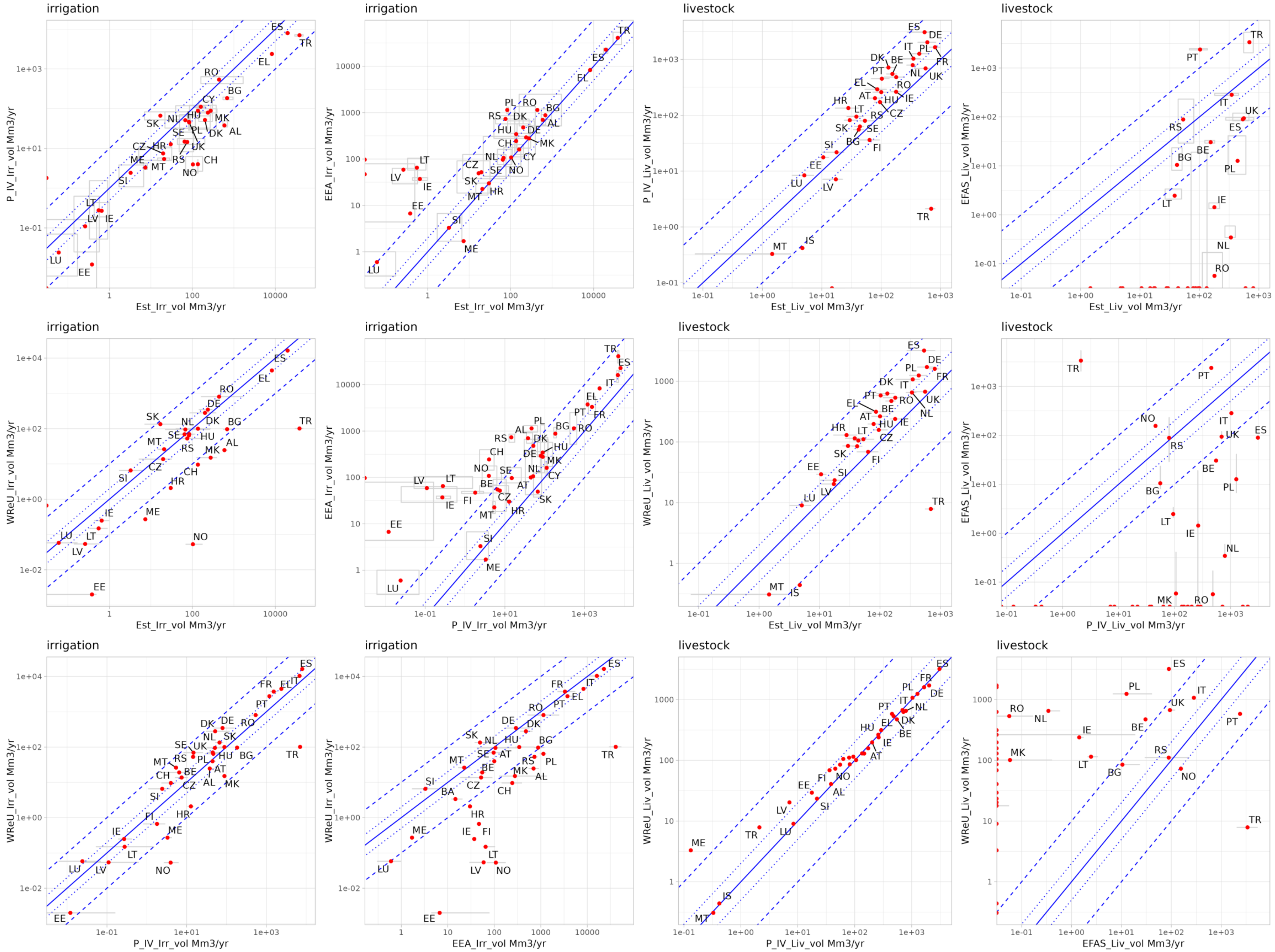
Source: JRC

Figure 16. Comparisons among energy (cooling) water use reported by Eurostat (Est) and the EEA, energy (cooling) water demand from the Water Reuse study considered in this report (WReU), energy (cooling) water demand in the PESETA IV project (P_IV) and EFAS and in the PPDB of the JRC. The dots represent the median of the time series for each country in the two datasets, while the boxes represent the respective ranges. Lines are factors 2 and 10 discrepancies.



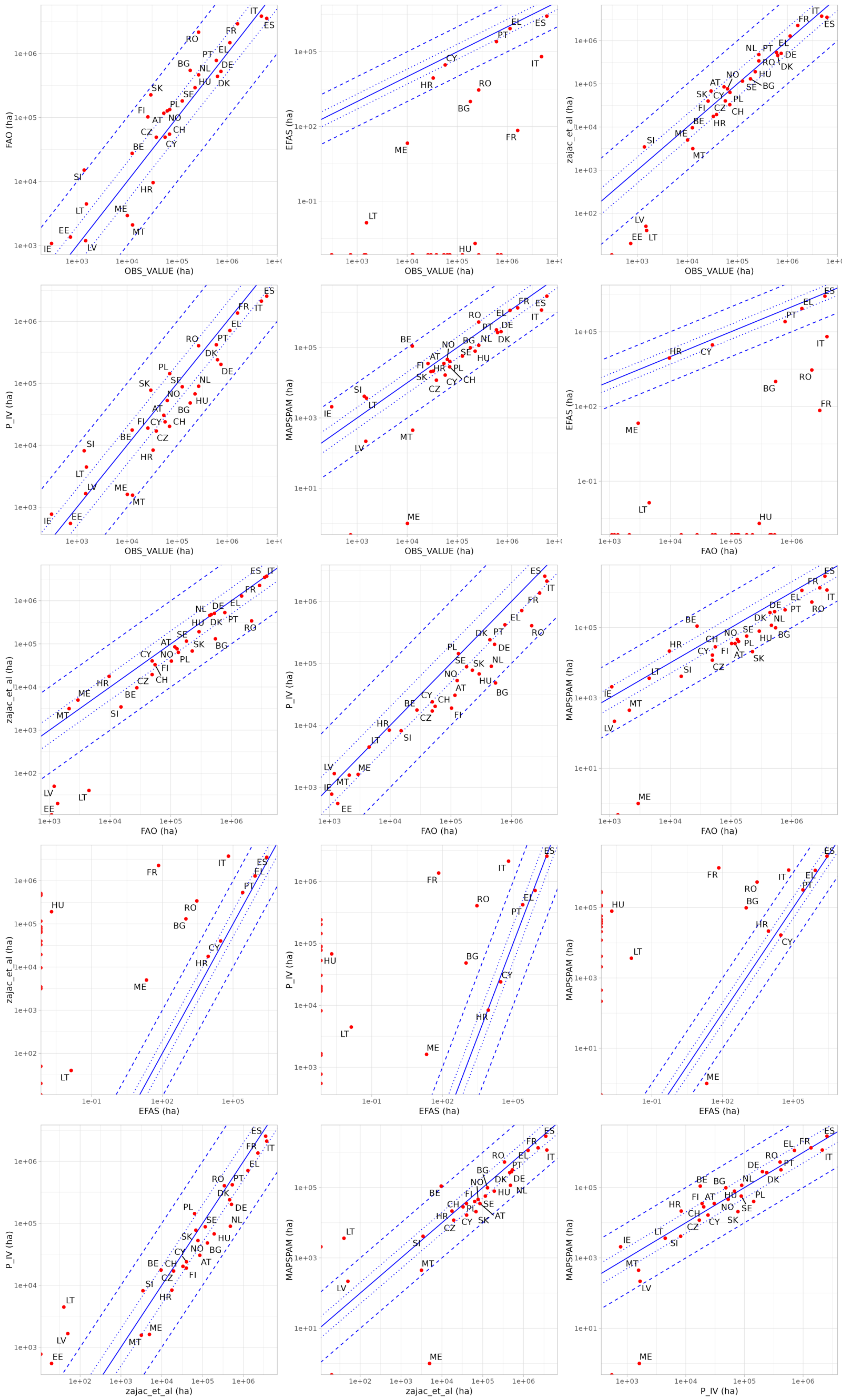
Source: JRC

Figure 17. Comparisons among water use for livestock and irrigation reported by Eurostat (Est) and the EEA, water demand for livestock and irrigation from the Water Reuse study considered so far in this report (WReU), and water demand for livestock and irrigation in the PESETA IV project (P_IV) . The dots represent the median of the time series for each country in the two datasets, while the boxes represent the respective ranges.



Source: JRC

Figure 18. Comparisons among estimates of irrigated area by country.



Source: JRC

Part of the discrepancy in estimated irrigation demand may owe to discrepancies in the irrigated area accounted for in the models. In **Figure 18** we compare irrigated areas across a set of available information sources including:

- the one used in the EFAS 5.0 setup, calculated as the class of land cover corresponding to permanently irrigated agricultural land in the Corine Land Cover dataset for 2018[19];
- the one of the PESETA IV model setup, based on the irrigation map of Wriedt et al., 2009;
- the map of total irrigated area according to FAO[20];
- the irrigation map of Zajac et al., 2022, updating the one of Wriedt et al., 2009;
- the estimated irrigated area in the MAPSPAM dataset[21];
- the statistics on irrigated area provided by Eurostat, considered as a benchmark or "observed value"[22].

The comparison highlights varying consistency among the different sources. The map of Zajac et al., 2022, shows a slightly better match with observations than the others, followed by the PESETA IV map, MAPSPAM and FAO. The map used in the EFAS 5.0 setup is on the contrary grossly underestimating irrigation area in some large irrigating countries (e.g. Italy and France). The map of Zajac et al., 2022, tends to consistently estimate a larger area than the others.

In **Figure 19**, we summarize the total demand for the 27 members of the EU (median in time) for the different sectors according to the various estimates discussed above. A more detailed account of the comparison among the estimates is provided for each EU Member state in Annex 1.

It is apparent that discrepancies can be quite high and may affect the conclusions on the ranking of water users, time trends and the evaluation of demand management measures in the various water-using sectors.

The analysis presented in Section 3 below is based on the assumed demand (section 2.3.1) that shows reasonable consistency with Eurostat and EEA estimates for all sectors.

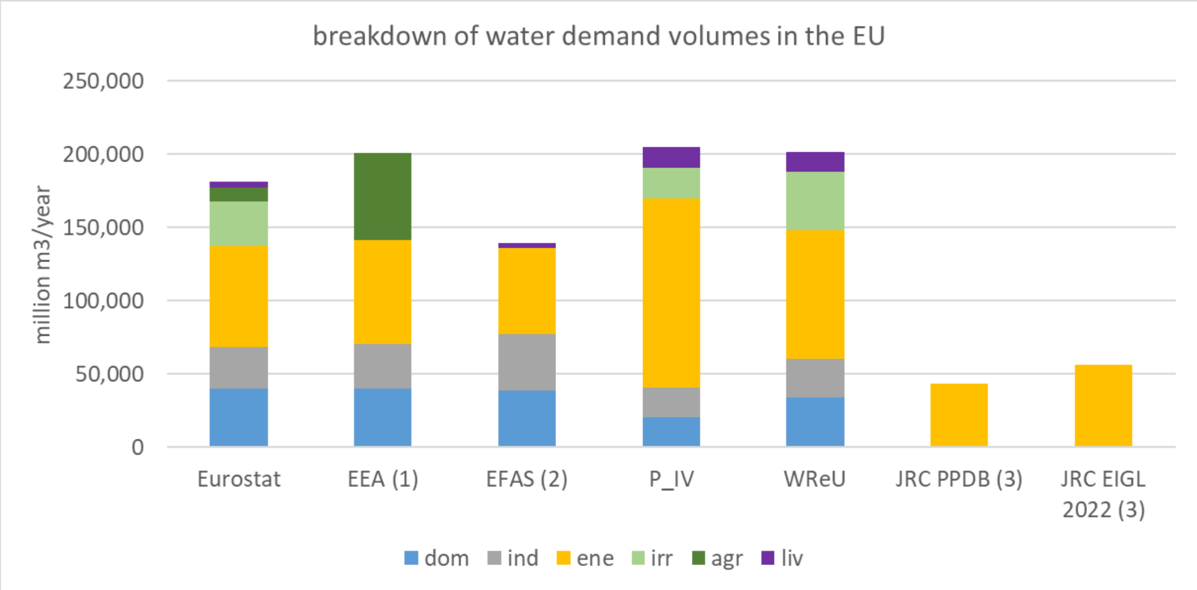
[19] https://land.copernicus.eu/en/products/corine-land-cover/clc2018

[20] https://www.fao.org/aquastat/en/geospatial-information/global-maps-irrigated-areas/latest-version

[21] https://mapspam.info/

[22] https://doi.org/10.2908/EF_POIRRIG

Figure 19. Breakdown of total EU water demand among the sectors considered in this study, according to different information sources. Notes: (1) Livestock not included. (2) Irrigation not included. (3) Only energy.



Source: JRC

2.4 Regional water appropriation indicators

The potential water appropriation can be aggregated in space (e.g. over a region, a country or the whole EU) based on the "center of mass" of water appropriations. If we consider a group of n river basins in a region, the regional appropriation index is:

Equation 8. Regional appropriation index weighted by demands

$$\alpha = \frac{\sum_{j=1}^{n} D_j \alpha_j}{\sum_{j=1}^{n} D_j}$$

The total potential appropriation of renewable water in a region can be computed also with reference to center of mass of availabilities as:

Equation 9. Regional appropriation index weighted by availability

$$\alpha' = \frac{\sum_{j=1}^{n} Q_j \alpha_j}{\sum_{j=1}^{n} Q_j}$$

Equation 8 gives more weight to those water resources on which demands impinge the most, while **Equation 9** gives more weight to the water bodies with highest availability in a region. Looking at the i-th sector, we can similarly compute for a region the demand-weighted appropriation of the water resources on which a sector relies:

Equation 10. Regional appropriation index of the water resources of each sector

$$\beta_i = \frac{\sum_{j=1}^{n} D_{ij} \alpha_j}{\sum_{j=1}^{n} D_{ij}}$$

For a given region, the vector $\{\beta_1, \ldots, \beta_s\}$ indicates the level of appropriation of *river basins* from which each sector is supposed to abstract water for their needs. The higher β_i, the more sector i sources water from highly appropriated river basins, hence arguably more exposed to competition for resources.

The sectorial contribution to water appropriation in the j-th river basin is given by the ratio $\alpha_{ij} = \frac{D_{ij}}{Q_j}$. The water appropriation of a river basin, α_j, is apparently the *sum* of sectorial appropriations α_{ij}. The sectorial contribution to water appropriation in a region is computed for the i-th sector as:

Equation 11. Regional sectorial appropriation index of the water resources of each sector

$$\gamma_i = \frac{\sum_{j=1}^{n} D_{ij}\alpha_{ij}}{\sum_{j=1}^{n} D_{ij}}$$

For a given region, the vector $\{\gamma_1, \dots, \gamma_s\}$ indicates the sectorial contributions to water appropriation in the river basins where each sector may abstract water. The closer γ_i to β_i, the more sector i contributes to the appropriation of the sector's source river basins. When $\frac{\gamma_i}{\beta_i}$ is close to 1, the i-th sector is a regional "game maker", i.e. the sector is largely responsible for water appropriation. When $\frac{\gamma_i}{\beta_i}$ is close to 0, the i-th sector is a "game taker", i.e. the sector is exposed to water appropriation mostly caused by other sectors. All intermediate values of $\frac{\gamma_i}{\beta_i}$ correspond to regions where responsibility for water appropriation is shared among more players.

In the following, we will make use of the above indicators to represent the characteristics of water appropriation across the EU, its Member States and regions. In order to compute the indicators, we estimate demand with the datasets shown in § 2.3.1 and availability as in § 2.2.1. It should be noted that the appropriation indicator can be often greater than 1, indicating that demand in a river basin exceeds availability. In such circumstances, obviously demand can be met only through reuse of resources previously withdrawn for other uses, or by transferring resources from other river basins.

3 Human appropriation of freshwater in Europe

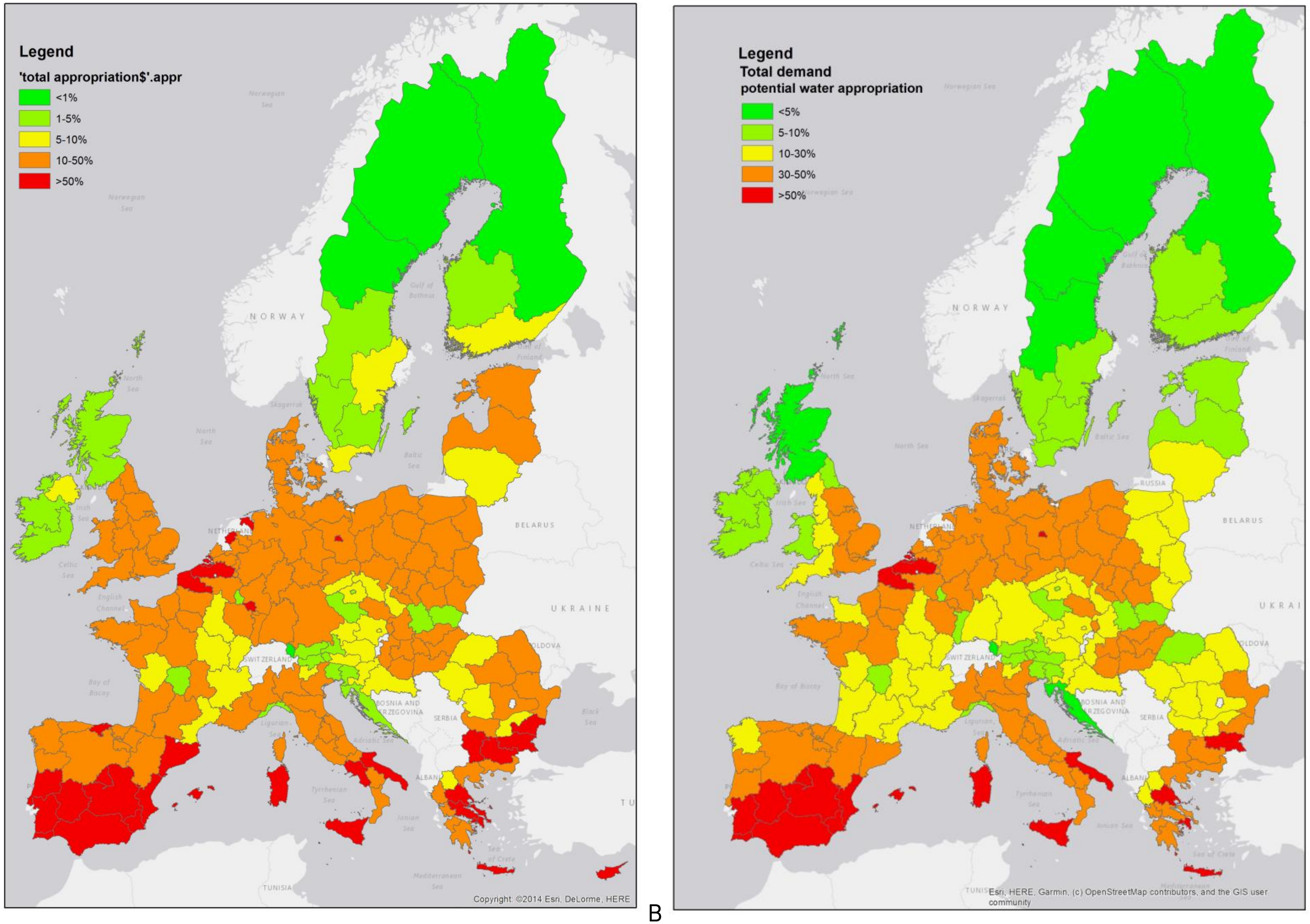
In this section, we provide a proof of concept of the use of indicators discussed in §2.4 to assess the state of human appropriation of water resources across Europe. The indicators can be computed under present conditions, and under a scenario of changed water availability following climate change (corresponding to RCP 4.5 and RCP 8.5 at the end of the XXI century), assuming no change in water demand. This assumption serves solely the purpose of exploring the effects of climatic trends, while demand will obviously evolve with climate and economic activities.

The total appropriation of blue water aggregated at regional level, weighted by demand (α, **Equation 8**) is shown in **Figure 20** A. Except for the northern regions of Sweden and Finland, α is always sizeable and mostly above 5% of renewable water resources. For most of the European regions α is in the range of 10 to 50 %, while in some southern European regions, in addition to some cases in the north-west, α exceeds 50% and, in a few cases, also 100% indicating potential severe pressure on water bodies. **Figure 20** B shows the total appropriation of blue water aggregated at regional level, weighted by availability (α', **Equation 9**) by level-2 NUTS regions in Europe. Similar to α, the indicator highlights areas with relatively high levels of appropriation both in southern Europe, and in an east-west belt from England to western Poland, reflecting the interplay of availability and demand. It should be borne in mind that appropriation in southern Europe may often correspond to higher levels of consumption, while in the North appropriation is often associated with large plant cooling, with generally lower levels of consumption.

The indicators of sectorial appropriation β_i (**Equation 10**) are always well correlated with the overall appropriation indicator α (**Figure 21**) and are not presented as maps here.

Figure 22 shows the sectorial appropriation indicators of regions γ_i, **Equation 11**. In the case of energy, appropriation (**Figure 22** A) is lower than total appropriation α (**Figure 20** A) in most of the central belt of Europe, in the eastern Iberian Peninsula, Denmark, western central Italy and western Greece. In the other regions of northern Europe, α is comparable to the sectorial potential appropriation for energy. Only in south-eastern France (region of Provence-Alpes-Côte d'Azur) the potential sectorial appropriation for energy is slightly higher than the total potential appropriation, indicating that river basins providing water for energy tend to be more exploited than the average of river basins in the region. For public water supply (**Figure 22** E) and for industry (**Figure 22** B), potential supply appropriation is always significantly lower than total appropriation (**Figure 20** A), with the exception of Madrid in central Spain where public supply potential appropriation is comparable with total potential appropriation. In the case of irrigation (**Figure 22** C) and livestock (**Figure 22** D), there is a clear pattern of sectorial appropriation comparable with total appropriation in many southern European regions, more pronounced for irrigation than for livestock. For the rest of Europe, sectorial appropriation tends to be systematically lower than total appropriation.

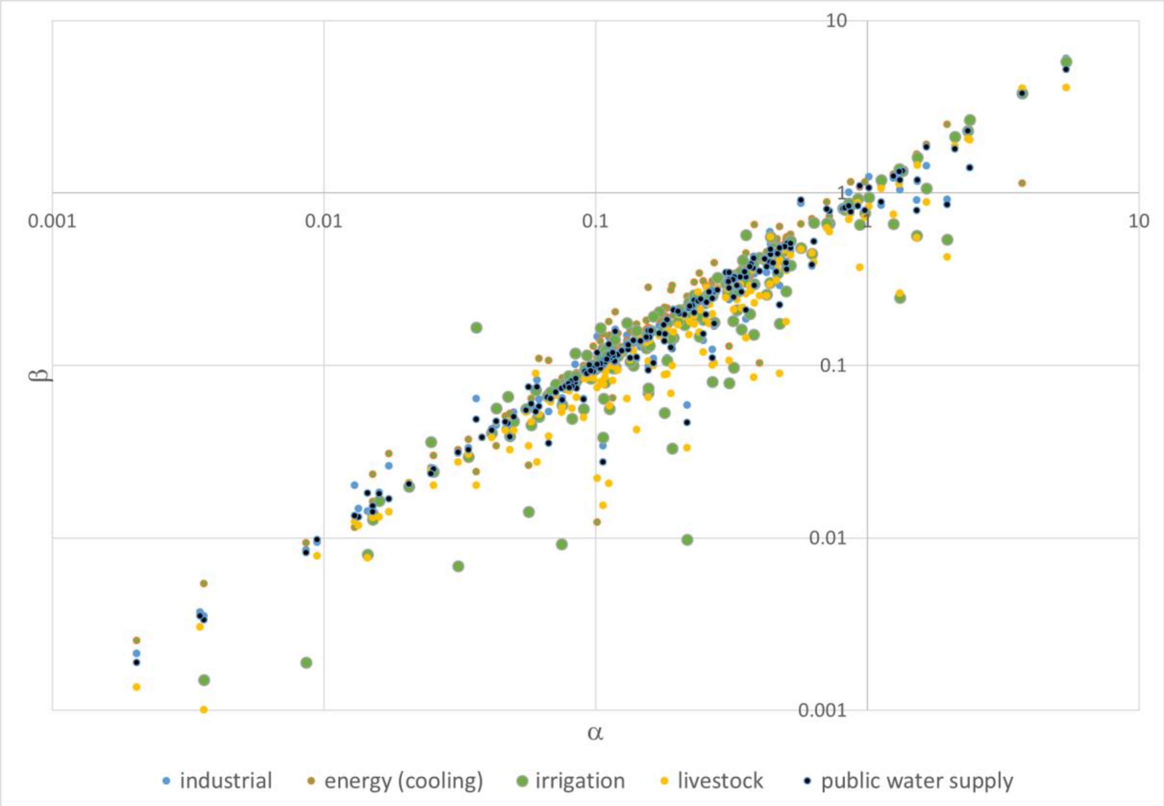
Figure 20. The water appropriation indicator following (A) Equation 8 and (B) Equation 9, by level-2 NUTS regions.



A B

Source: JRC

Figure 21. Comparison of indicators α and β_i for the sectors considered.



Source: JRC

The correlation of total with sectorial appropriation indicators (**Table 4**) shows links between total and irrigation, and livestock and irrigation potential appropriation, while the other sectorial appropriations are less closely related. Individually, industrial sectorial potential appropriation explains 14.7% of the variance of total potential appropriation, energy 18.7%, public supply 32.2%, while irrigation explains 80.1% and livestock 68.3%. Given the relatively low intensity of livestock appropriation compared with irrigation, and their mutual correlation, we may argue that irrigation appears to be the main overall explanatory factor of potential appropriation in Europe. However, the variability of conditions across Europe is high.

Table 4. Correlation matrix of regionally aggregated total and sectorial potential appropriation.

	α	$\gamma_{industry}$	γ_{energy}	$\gamma_{irrigation}$	$\gamma_{livestock}$
$\gamma_{industry}$	0.38	-	-	-	-
γ_{energy}	0.43	0.31	-	-	-
$\gamma_{irrigation}$	0.89	0.20	0.06	-	-
$\gamma_{livestock}$	0.83	0.22	0.01	0.89	-
$\gamma_{public\ supply}$	0.57	0.39	0.20	0.40	0.33

Source: JRC

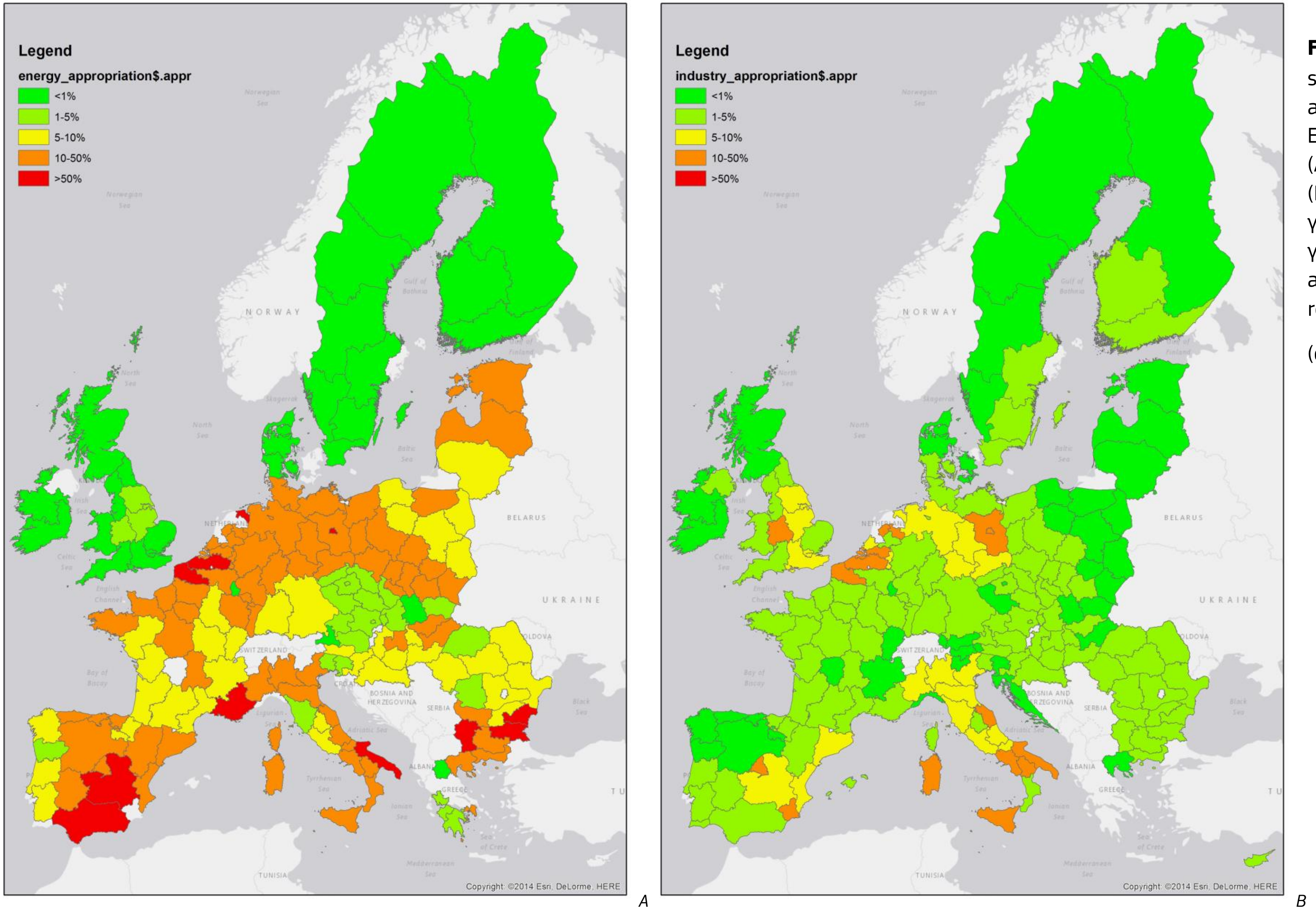


Figure 22. Maps of the sectorial potential appropriations of Equation 11 (γenergy (A), γindustry (B),γirrigation (C), γlivestock (D), γpublic$_{_supply}$ (E)) aggregated at European regional level.

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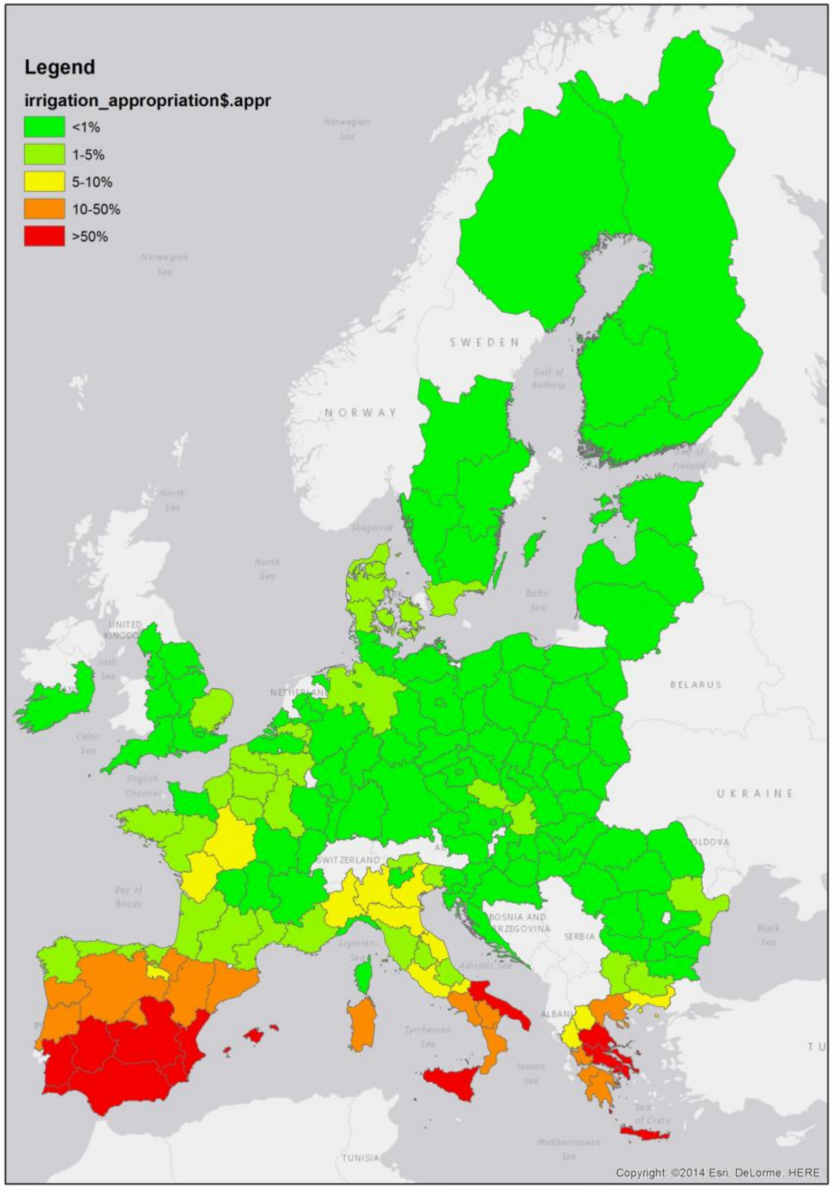
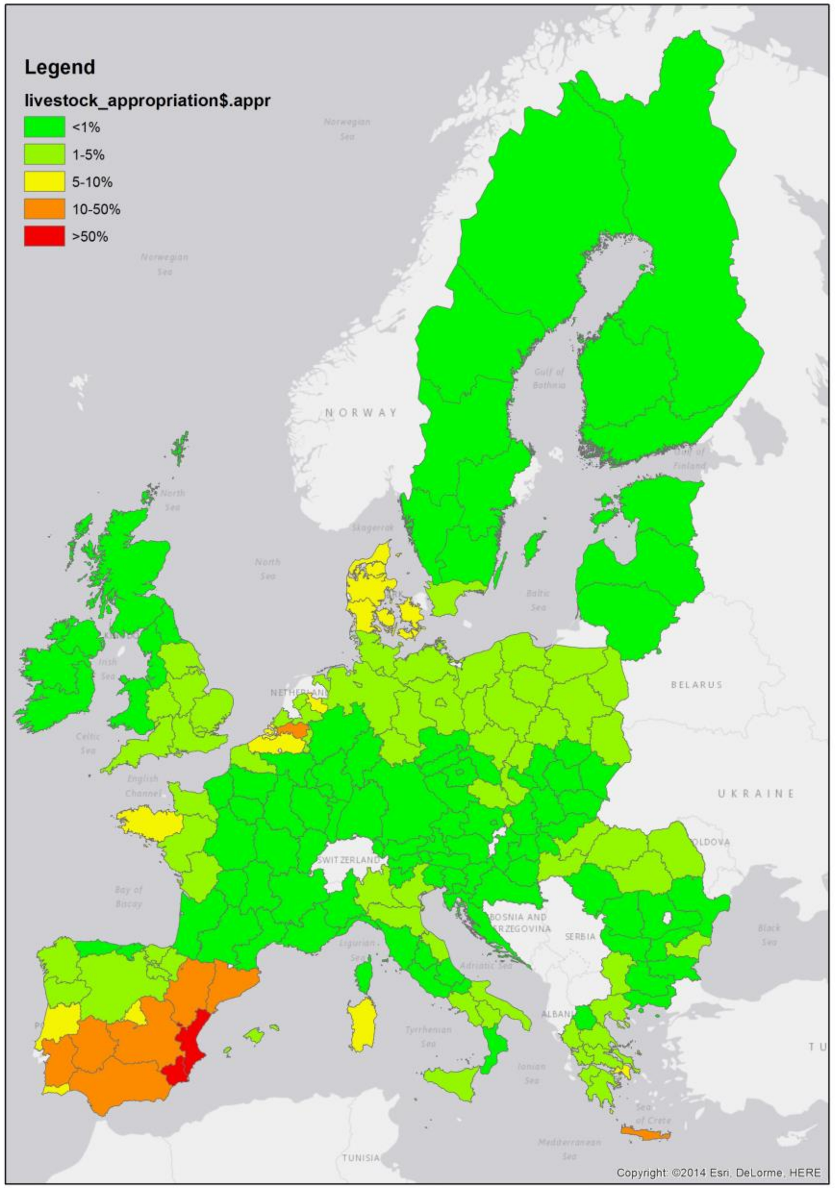


C



D

Figure 22. Maps of the sectorial potential appropriations of Equation 11 (γenergy (A), γindustry (B),γirrigation (C), γlivestock (D), $γpublic_{supply}$ (E)) aggregated at European regional level.

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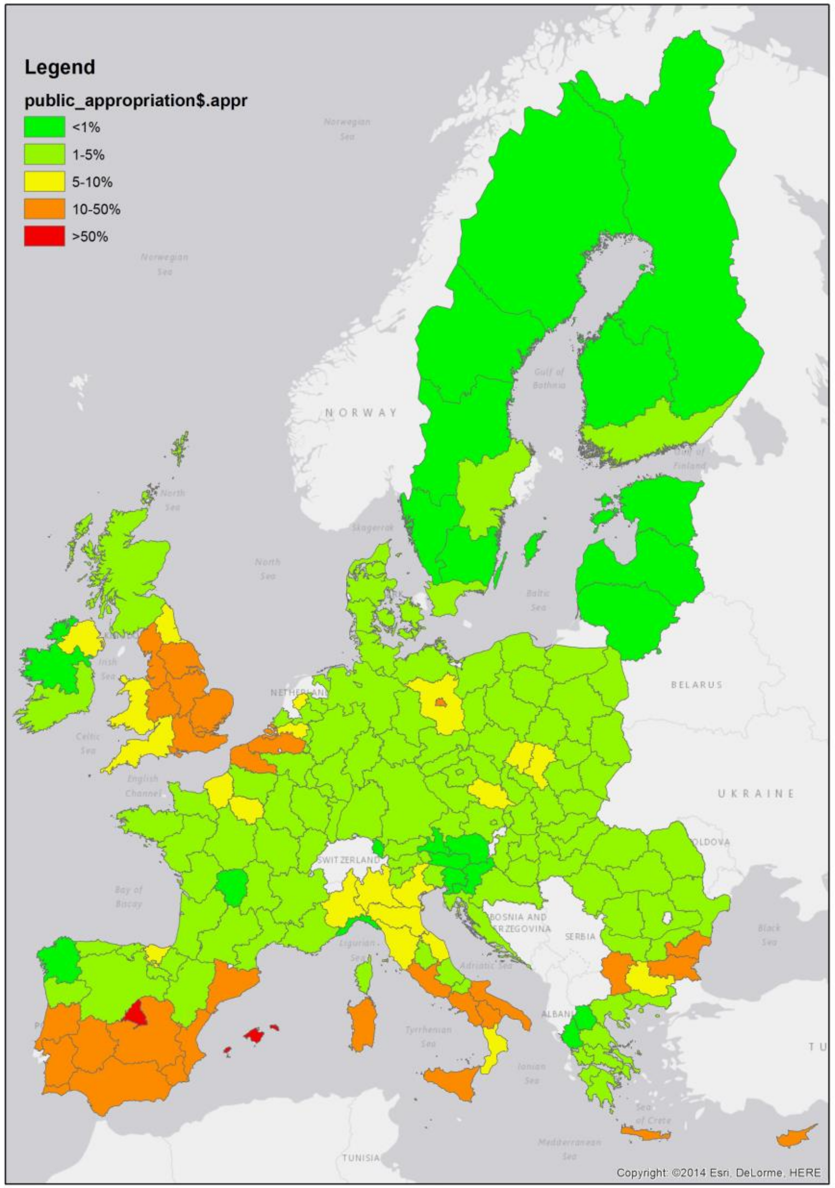
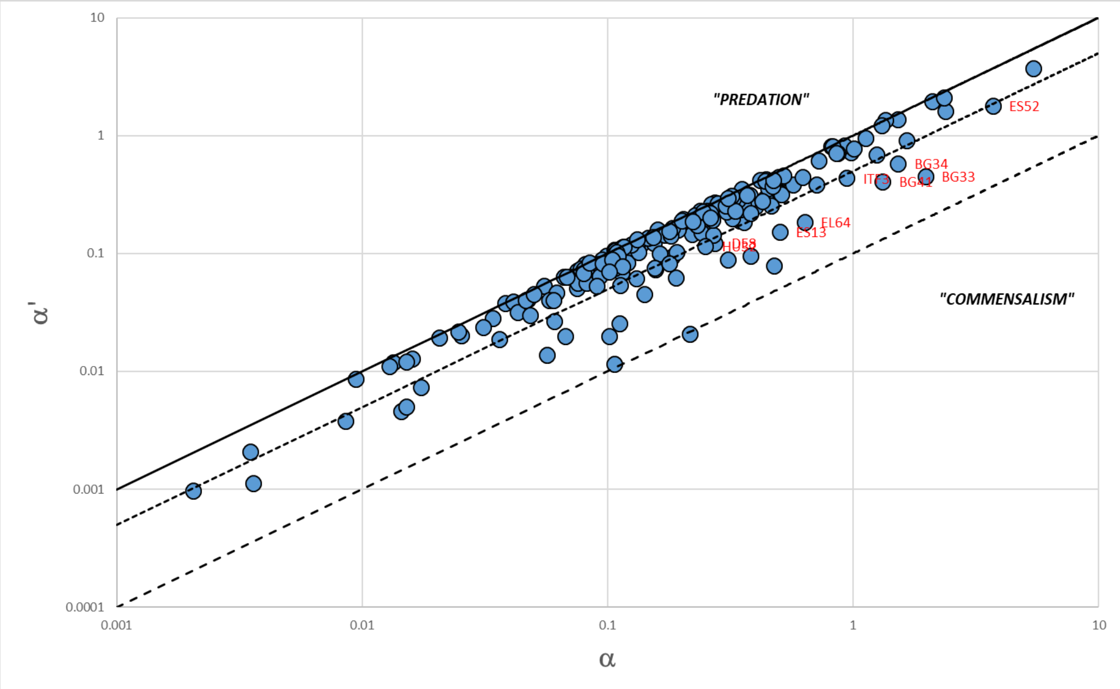


Figure 22. Maps of the sectorial potential appropriations of Equation 11 (γ_{energy} (A), $\gamma_{industry}$ (B),$\gamma_{irrigation}$ (C), $\gamma_{livestock}$ (D), γ_{public_supply} (E)) aggregated at European regional level.

E *Source: JRC*

Indicators α and α' are well correlated. This case can be described as widespread *"predation"* of water resources in the region. A region with $\alpha' << \alpha$, however, indicates that highly appropriated river basins coexist with river basins with low demand and lower appropriation. This case corresponds to regions with a form of *"commensalism"* between human and ecosystems use of resources. **Figure 23** shows that regions in Bulgaria, Germany, Greece, Spain, Hungary and Italy have an overall appropriation α'>10% but α'/α <0.5, thus exhibiting a degree of "commensalism".

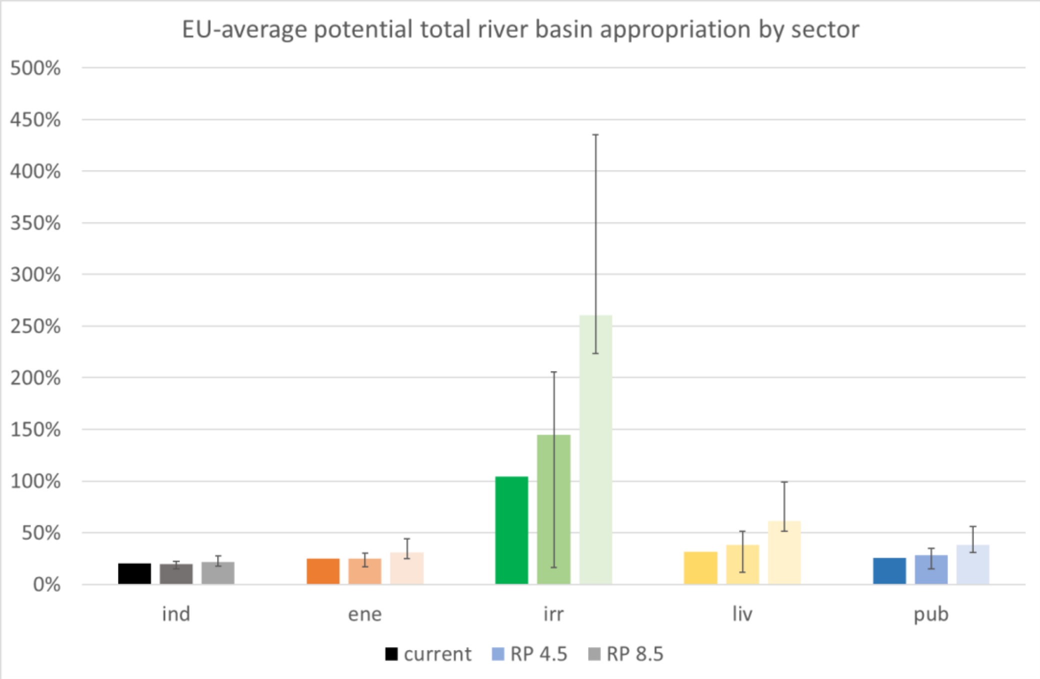
Figure 23. Comparison of α and α'. Regions with α'>10% but α'/α <0.5 are Severoiztochen (BG33), Yugoiztochen (BG34), Yugozapaden (BG41), Mecklenburg-Vorpommern (DE8), Sterea Ellada (EL64), Cantabria (ES13), Comunitat Valenciana (ES52), Észak-Alföld (HU32), Campania (ITF3)



Source: JRC

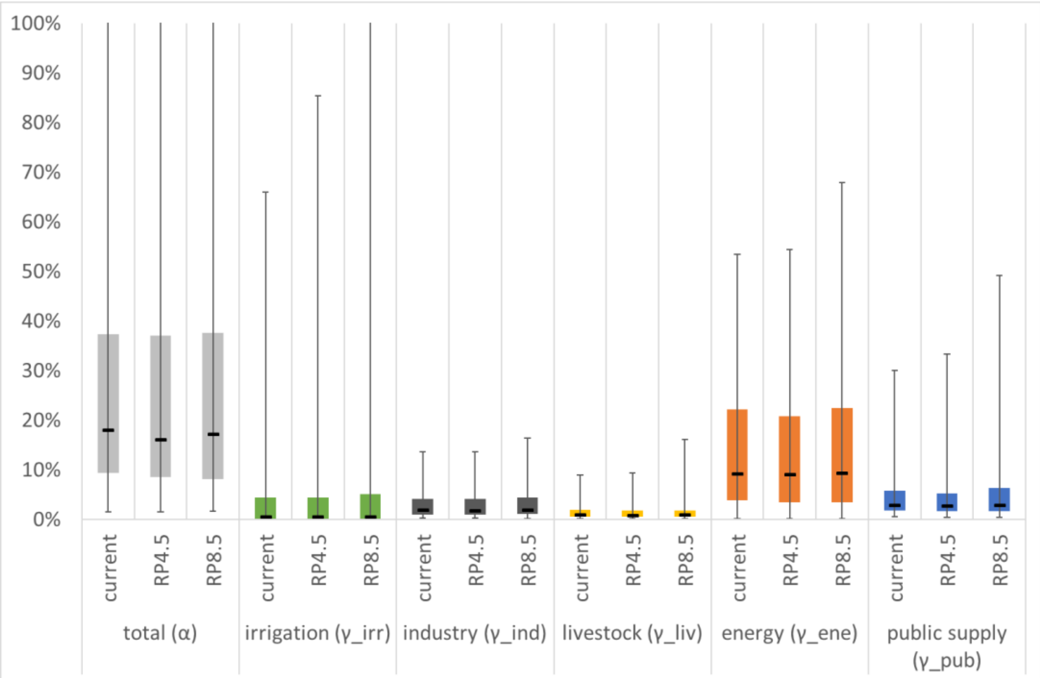
The appropriation of sectorial supplies, aggregated at the European Union level, is shown in **Figure 24**. In the aggregation, the intensity of demand in the different regions is used as a weight, hence the total potential appropriation in those river basins where each sector's demand is highest counts more. The potential appropriation of supplies for irrigation is the highest, well above the European median value of total appropriation around 15% (see Figure 25), with a value just above 100%, driven by the dominant demand in water-scarce regions such as the south of Spain. The total potential appropriation of supplies for the other sectors is instead consistent with this European median value. If we consider climate change scenarios, while irrigation is projected to undergo a dramatic increase, the livestock sector is also expected to undergo an increase in potential appropriation of supplies higher than the other sectors.

Figure 24. Total appropriation of sectorial supplies (β_{energy}, $\beta_{industry}$, $\beta_{irrigation}$, $\beta_{livestock}$, β_{public_supply}) aggregated at European level. RCP 4.5 and RCP 8.5 scenarios are the median of model projections, with error bars indicating the range of variability. The box is the interquartile range and the whiskers are the 5-95% interval of values calculated for NUTS2 regions.



Source: JRC

Figure 25. Box plot of the values of total and sectorial potential appropriation at European level as shown in **Figure 20** and **Figure 22**, respectively. RP 4.5 and RP 8.5 scenarios are the median of model projections. The box is the interquartile range and the whiskers are the 5-95% interval of values calculated for NUTS2 regions.



Source: JRC

Figure 25 shows box plots of the distribution of the regional values of α, with an interquartile range of approximately 10-40%, and median just above 15%. It also shows the box plots for current and projected indicators of sectorial appropriation as in the case of total appropriation.

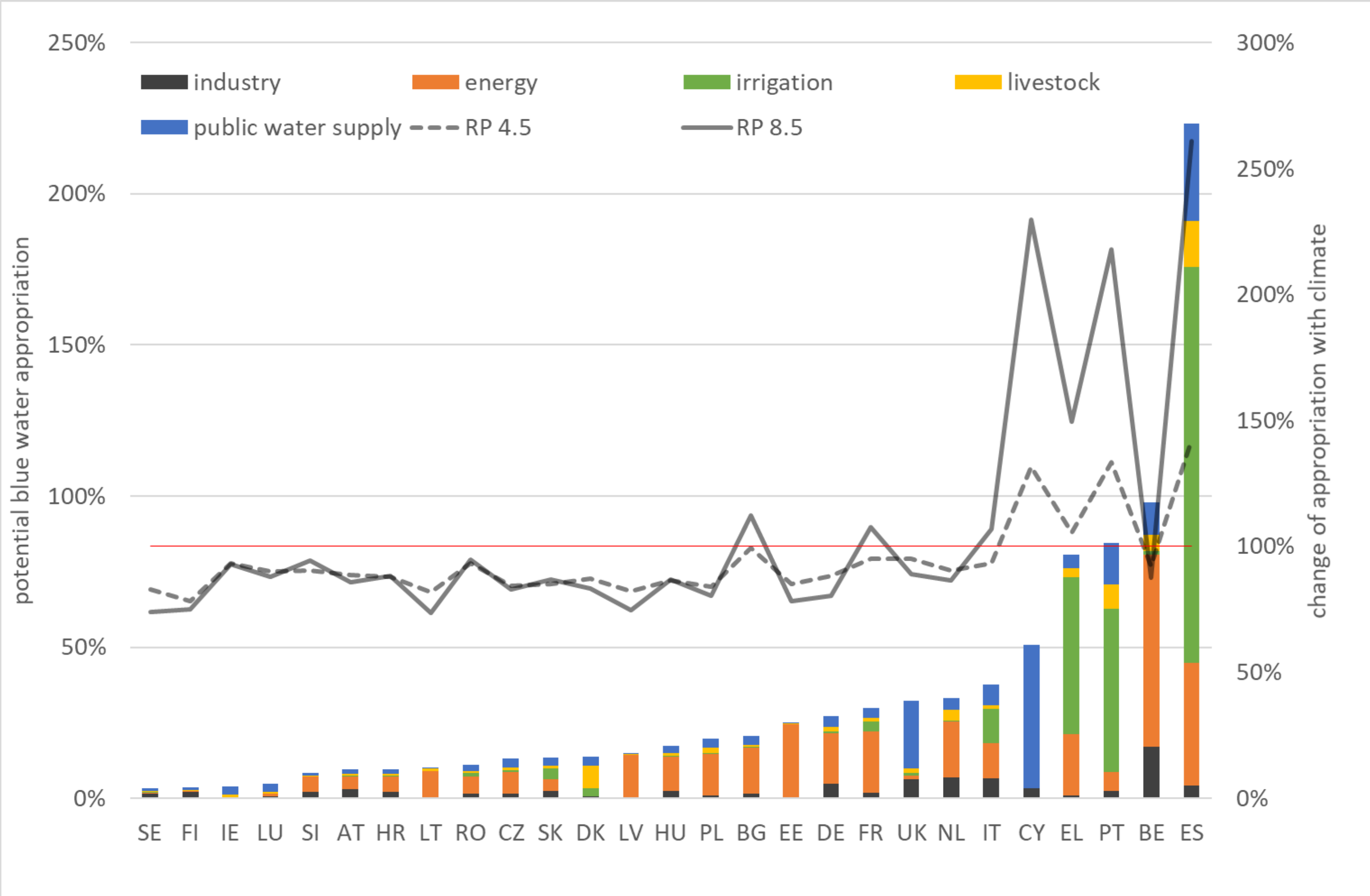
Total appropriation α (**Equation 8**) is projected to change under climate scenarios, reflecting lower availability in the south of Europe, and higher in the north, however highlighting modest changes when aggregated at European scale due to compensation. As Europe is projected to experience an increase of blue water availability in the north, and a decrease in the south, the overall effect is relatively modest in the majority of the regions.

The EU-aggregated values of γ_i show an interquartile range (**Figure 25**) well below 10% except for energy, where the range is approximately 5 to 25%. However, the 95th percentile is comparable to the one of total potential appropriation, highest for irrigation followed by energy and public supply. Livestock and industrial use have significantly lower values. It is worth noticing that climate change may increase appropriation extremes (95th percentiles increasing) for all sectors. In **Figure 26** we plot the stack of sectorial appropriation indicators (eq. 3) by country. The sum of the sectorial potential appropriations, as shown in the graph, does not necessarily correspond to the total potential appropriation and is in general higher than the latter. However, it is an indicator of the overall level of appropriation. At the same time, the individual vector components reflect the main drivers of potential appropriation by country. The country with highest sum of sectorial potential appropriation is Spain (ES), where irrigation is the highest followed by energy, public supply and, to a lesser extent, livestock. Similar patterns appear for Greece (EL) and Portugal (PT). Cyprus (CY) shows very high sum of sectorial potential appropriations, *a fortiori* because irrigation is not included in the analysis for this country. Belgium (BE) is the second-highest country in terms of sum of sectorial appropriation, with a clear dominance of energy. Italy (IT) comes as the fifth highest in the ranking, but with sectorial demands much more uniformly distributed. The potential appropriation in the UK is dominated by public supply, while the Netherlands (NL), Germany (DE) and France (FR) present a high share of potential appropriation by the energy sector, just like most of the other countries. Denmark (DK) presents high potential appropriation by the livestock sector. Sweden (SE) and Finland (FI) have the lowest sum of sectorial potential appropriations.

Figure 26 also plots changes in total potential appropriation due to changes in blue water availability, highlighting the largest overall changes in Spain, Cyprus, Portugal and Greece and, to a lesser extent, in Italy, France and Bulgaria.

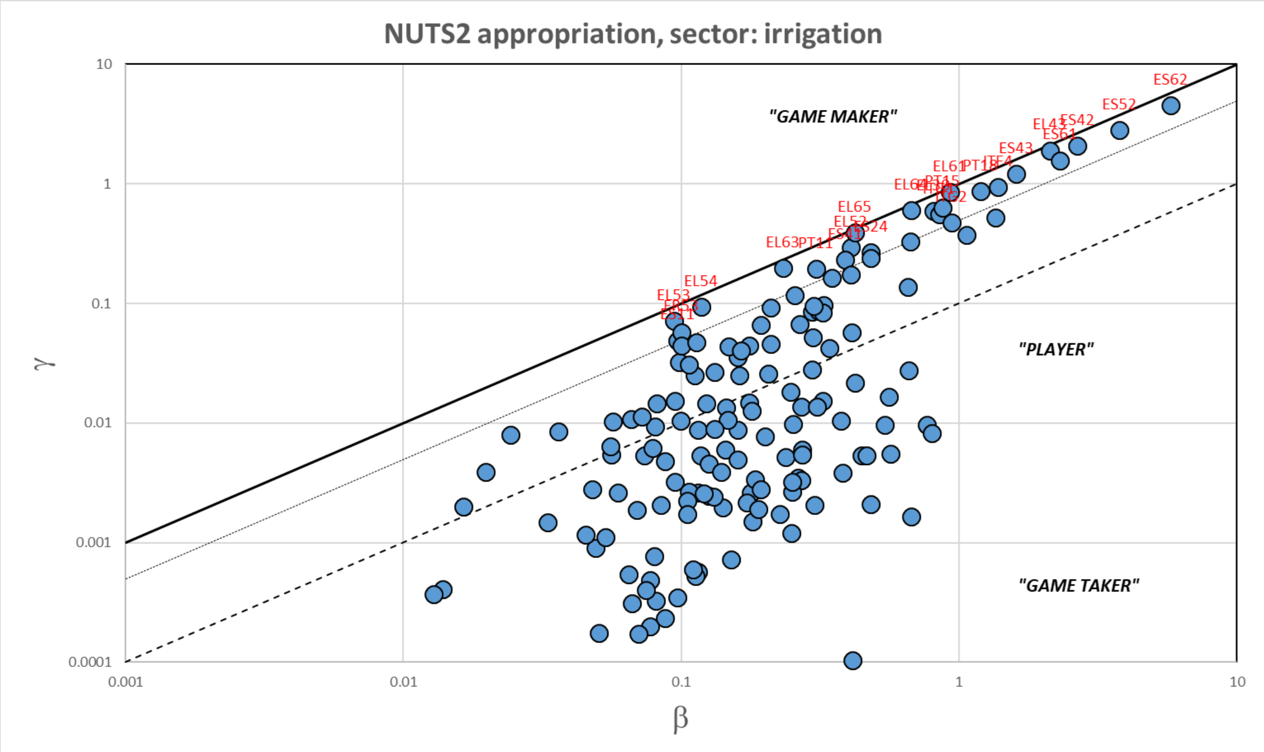
Figure 27 shows a comparison of β_i and γ_i for the five sectors considered, highlighting the regions where each sector is a “game maker”, a player among others or a “game taker”. The graphs show the 1:1, 2:1 and 10:1 lines to guide the judgment. Livestock and industrial use are never a game maker. Livestock is most often a “game taker”, while industry is a player in several regions. Irrigation and energy show a more polarized pattern: they are clear game makers in the regions where they are substantially present, while in several regions their role is marginal. Domestic water demand is almost always a player but not so often a “game maker”.

Figure 26. Combinations of sectorial potential appropriations (γenergy, γindustry, γirrigation, γlivestock, γpublic_supply) by country in the EU. For the codes of the countries. RP 4.5 and RP 8.5 scenarios are the median of model projections (mean 2070-2100). For country codes: http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Country_codes



Source: JRC

Figure 27. Comparison of β and γ for each of the 5 sectors considered. (continues)



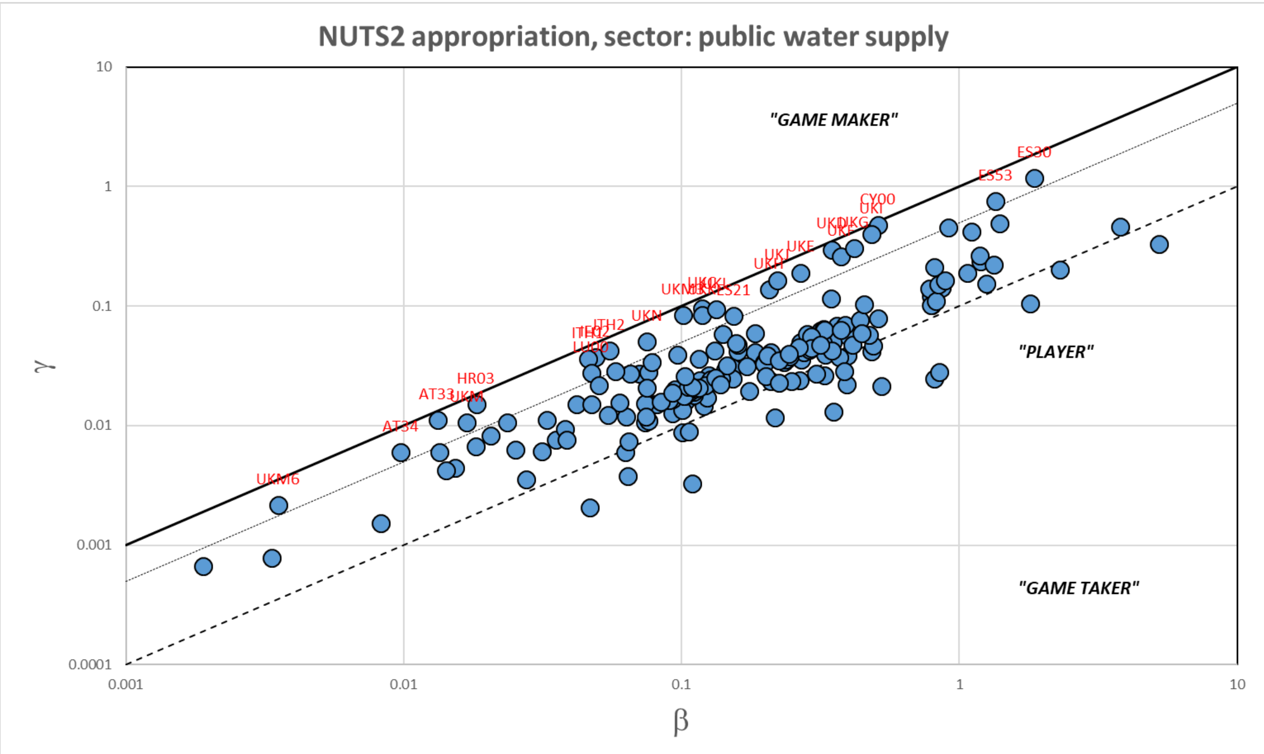
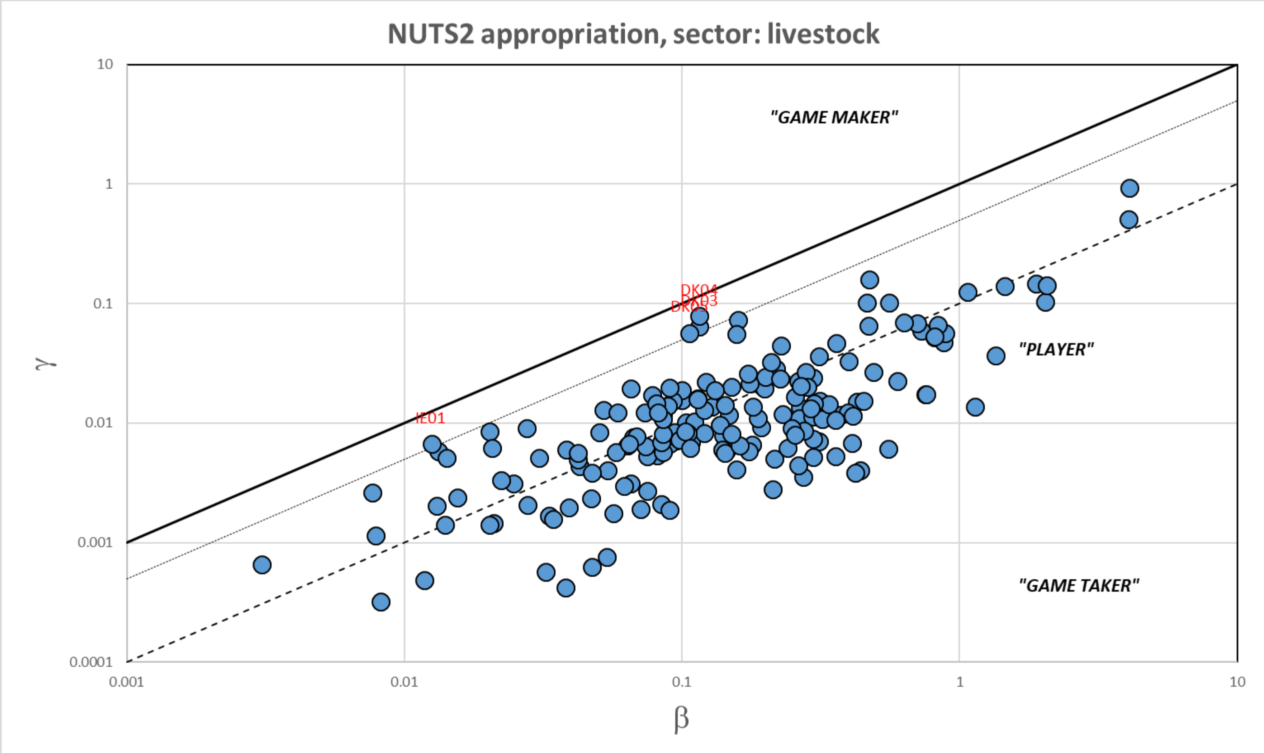


Figure 27. Comparison of β and γ for each of the 5 sectors considered. (continues)



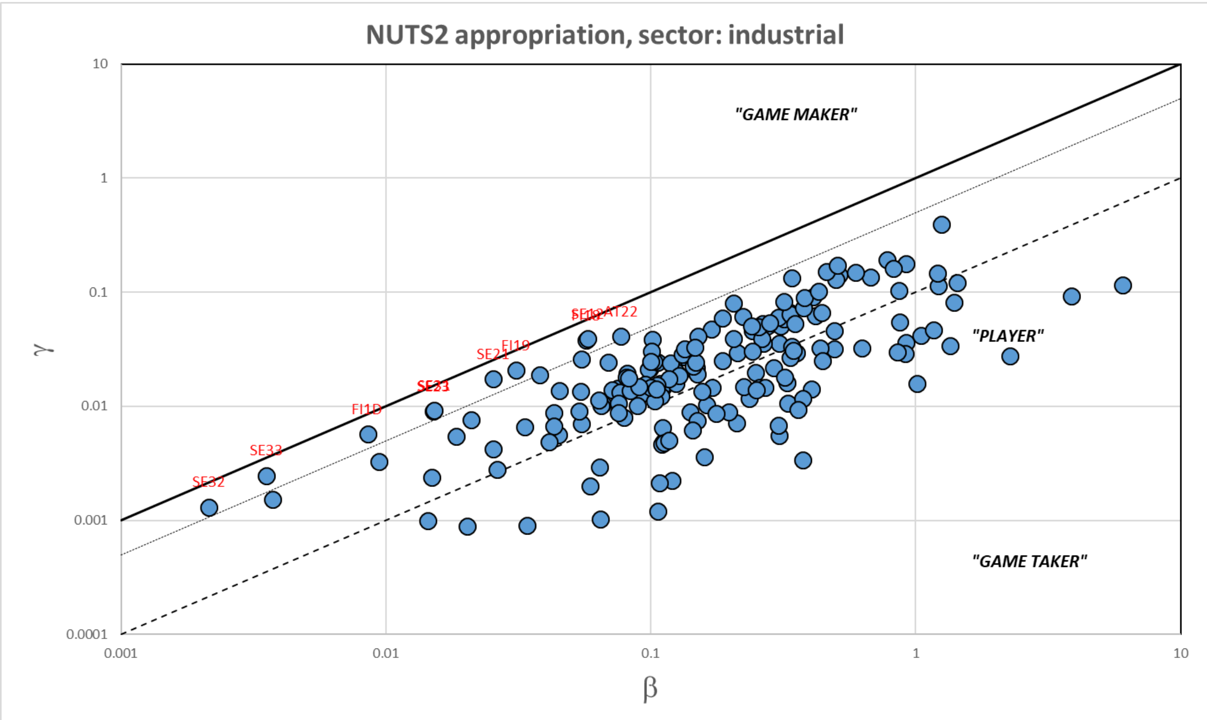


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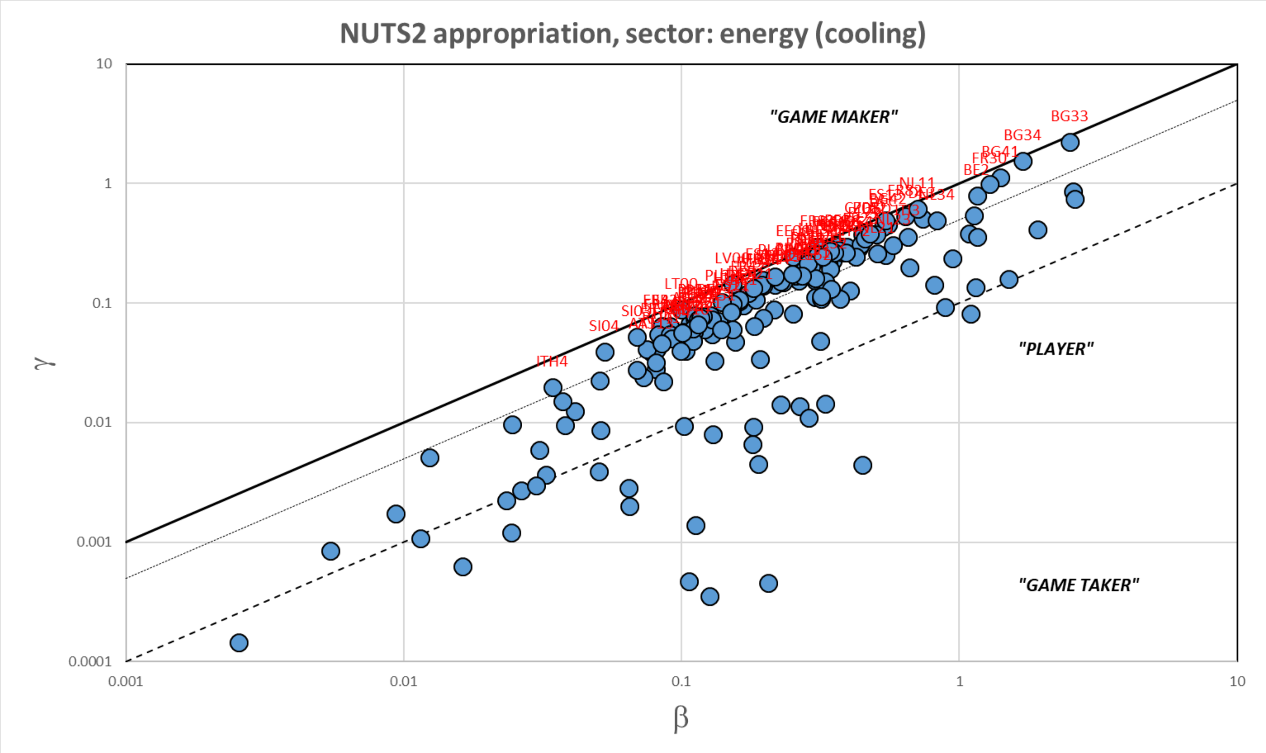
Figure 27. Comparison of β and γ for each of the 5 sectors considered.



Source: JRC

4 Opportunities for water reuse

In the previous sections, we have proposed a characterization of water appropriation in Europe highlighting situations of potential competition and stress on aquatic ecosystems caused by high abstractions from the streams. Abstractions may be reduced by reusing some of the water for multiple purposes. Water reuse in a “beneficiary” sector after first use by another “donor” sector entails appropriate management and costs, the most obvious being cost of treatment, transfer and pumping. These costs may be kept in check whenever the “beneficiary” sector’s users are downstream and close enough to the users in the “donor” sector. In order to understand how the five sectors considered here are positioned relative to each other, we refer to the indicator of the sector demand’s weighted-average distance to the catchment outlet, i.e. for the generic i^{th} sector and j^{th} catchment:

Equation 12. Sector demand’s distance to outlet

$$L_{i,j} = \frac{\int_{A_j} L(x,y) D_i(x,y) dx\, dy}{\int_{A_j} D_i(x,y) dx\, dy}$$

where $L(x,y)$ is the downstream flow length (see Pistocchi, 2014) at location (x,y) within the catchment, $D_i(x,y)$ the demand of the i^{th} sector at (x,y) and A_j is the area of the catchment. The above indicator is the average distance that water used for a sector’s demand must travel along the stream network before it reaches the outlet. It can be calculated on a continuous basis along the stream network using the ArcGIS Spatial Analyst 10.7 © standard weighted downstream flow length operator (see §2.1). The weighted average distance between demands in sectors *p* and *q* in the j^{th} catchment is simply:

Equation 13. Inter-sector distance in a catchment

$$L_{p,q,j} = L_{pj} - L_{q,j}$$

Figure 28 shows the calculated distance between demands for the European catchments used in this analysis. Along with the spatial distribution of distances, it shows the cumulative demand volume distribution as a function of distance, both of the “donor” sector, and of the “beneficiary” sector. The cumulative demand volumes at zero distance (when the cumulates cross the y-axis) are indicative of the volumes of the second sector that could be reused in the first sector, while the volumes to the right of the y-axis are indicative of the volumes in the first sector that could be reused in the second sector. After irrigation, obviously we cannot expect significant reuse as the demand is largely consumptive.

For energy, about 30 billion cubic meters per year are on average upstream of irrigation, which in turn demands about the same volume (Figure 28 A), suggesting ample potential to meet irrigation demand after use for energy. The river basins with a favourable distribution of the two demands are widespread across Europe, including in some southern regions where the irrigation demand is highest. In many cases, water used for the cooling of energy plants is arguably already reused downstream. The coexistence of these two large water-using sectors in several basins may cause the appropriation index to exceed 1 (for example, in catchments of the Iberian peninsula).

For industry, about 10 billion cubic meters are upstream of irrigation demand, which could cover about a half of the ca. 20 billion cubic meters required for irrigation downstream (Figure 28 B). Favorable configurations are more widespread than in the case of energy across Europe. Industrial water, though, may pose more significant challenges than water used for cooling when it comes to water quality issues, and an assessment of the actual possibility to reuse industrial water in irrigation requires more specific considerations. A similar pattern appears also when looking at the reuse of domestic water (public water supply) for irrigation (Figure 28 C). In this case, the quantity that could be reused is larger, and water quality issues may be less constraining than for certain industrial sectors, domestic water reuse being already identified as an important source of water for irrigation and disciplined by EU Regulation 741/2020. Domestic and industrial water demands are also favorably located for reuse in the cooling of energy plants (Figure 28 D, E), although the reusable volumes in this case are only about a quarter of what is needed for cooling. Moreover, domestic and industrial water may feature higher temperature than ambient water, limiting their usability for cooling.

While this analysis is indicative and does not aim at quantifying the volumes concretely available at specific locations, it shows a widespread opportunity for reducing abstractions through water reuse. In certain cases, reuse for energy prior to further use in irrigation could be also an opportunity to maximize water resilience while minimizing abstractions.

Figure 28. Average downstream distance between sectors. (A) energy/irrigation, (B) industry/irrigation, (C) public water supply/irrigation, (D) public water supply/energy, (E) energy/industry.

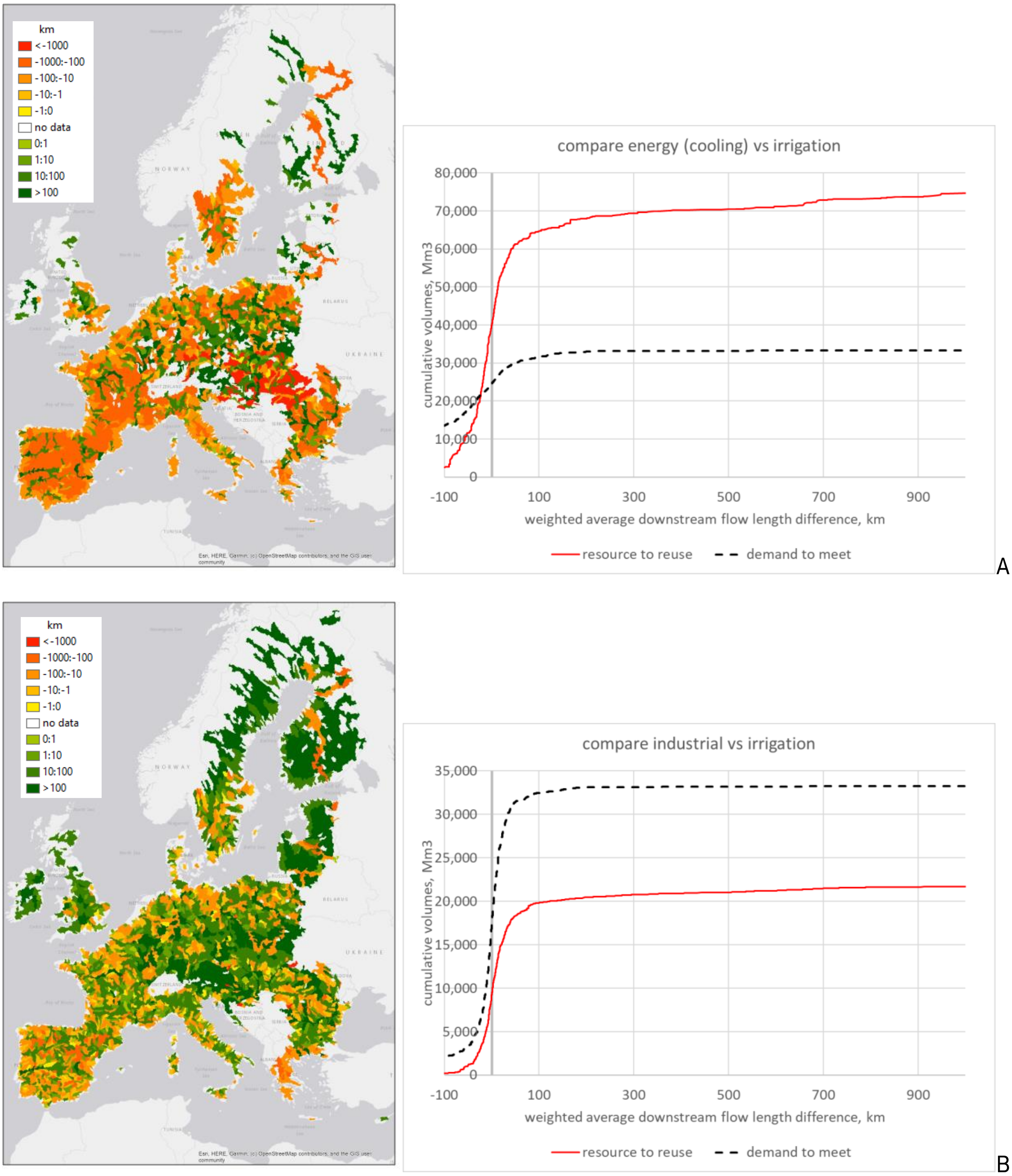


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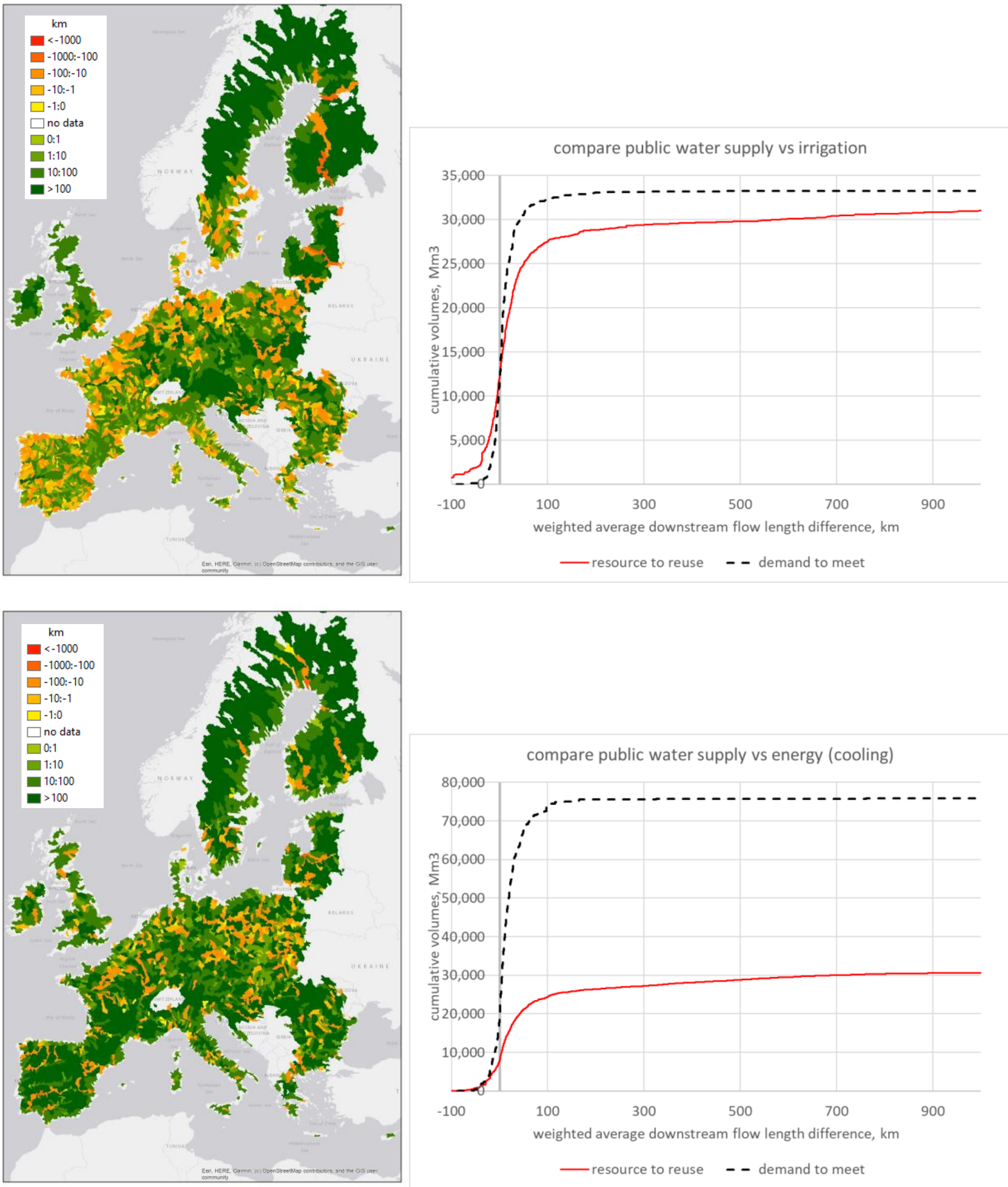
Figure 28. Average downstream distance between sectors. (A) energy/irrigation, (B) industry/irrigation, (C) public water supply/irrigation, (D) public water supply/energy, (E) energy/industry.



C

D

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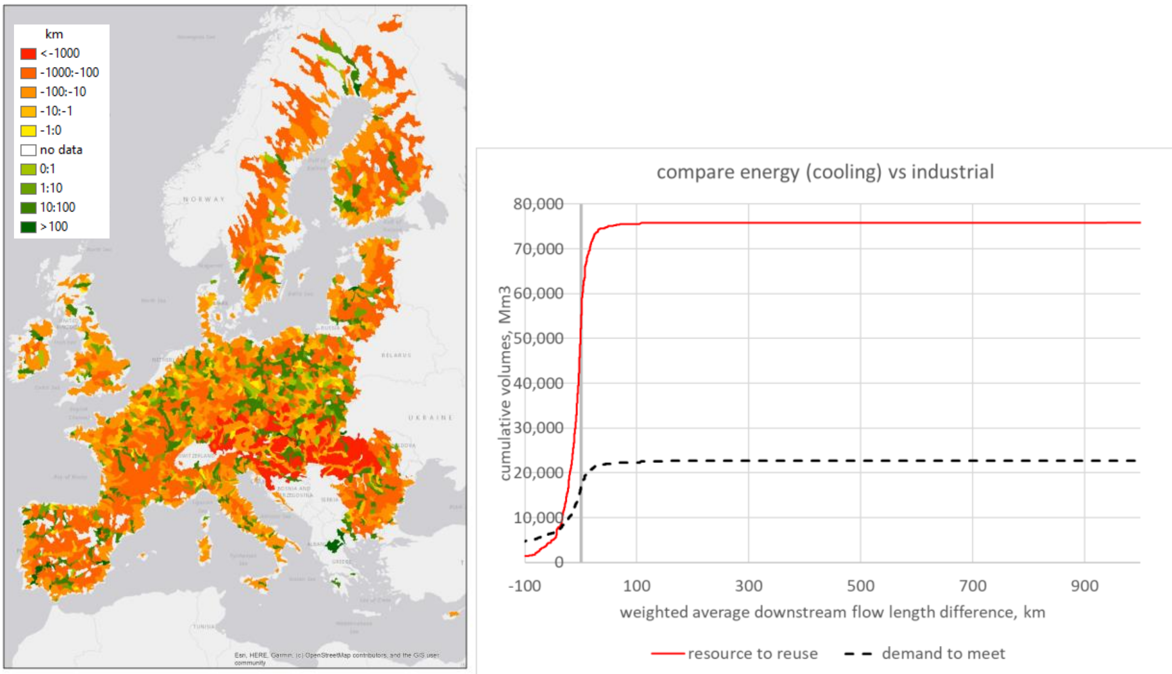
Figure 28. Average downstream distance between sectors. (A) energy/irrigation, (B) industry/irrigation, (C) public water supply/irrigation, (D) public water supply/energy, (E) energy/industry. the first sector mentioned is the “donor” (resource to reuse), while the second is the receptor (demand to meet)



E

Source: JRC

5 The case of reclaimed urban wastewater reuse for irrigation

5.1 Reduction of water appropriation through water reuse

Domestic wastewater reuse for irrigation is particularly in the focus of EU policy, and its potential has been assessed in Pistocchi et al., 2017. In order to appraise the potential of water reuse to reduce water stress, we compute the water appropriation indicator weighted by available volumes (**Equation 9**) after subtracting from the irrigation demand the amount of water potentially reused. For the latter, we take the estimation presented in Pistocchi et al., 2017 of the total volume of reclaimed wastewater potentially deployed for irrigation, without considering cost restrictions. **Figure 29** shows the distribution of the cumulative volume of water potentially allocated for reuse in the catchment upstream of each sub-basin, which represents a “negative demand” when calculating water appropriation. The potential of water reuse to mitigate water stress can be computed as the percentage variation of the appropriation indicator of **Equation 9**, between baseline conditions and a scenario of water reuse. **Figure 30** shows the distribution of the reuse mitigation potential by level-2 NUTS regions.

The reuse mitigation potential is summarized at country level as shown in **Figure 31**, and further in detail by regions from **Figure 43** to **Figure 53** in Annex 2. It should be noted that the indicator is the weighted average of the indicators computed for all river basins in the country, with higher weights given to river basins with higher water surplus.

5.2 Prioritization of areas for water reuse

Pistocchi et al., 2017, examined the potential cost and benefit for water reuse under different angles. In this section, we propose a tentative synthesis of the information in order to identify areas with significant co-benefits of water reuse across Europe, based on the findings in Pistocchi et al., 2017. A full prioritization of investments in water reuse is beyond the scope of this exercise, as it would require extensive verification of local conditions and an effective involvement of stakeholders and decision makers. In the following, we present a proof of concept for the prioritization of water reuse investments. The considerations presented below have an indicative aim and obviously do not replace a subsequent, more detailed evaluation.

Here we assume that a priority for water reuse in a region may be generated by the co-existence of some of the following criteria (Figure 32):

- Reuse may be an effective measure to reduce the stress on water resources due to existing water demand;
- Reuse may be an effective measure to reduce the load of nutrients to water bodies, by diverting nutrient flows to agriculture through simultaneous fertilization and irrigation (“fertigation”)[23];

[23] From a river basin management point of view, water reuse allows diverting flows of nutrients, from direct discharge to rivers to application to agricultural soils with irrigation. Fertirrigation (simultaneous application of fertilizers and water to plants) may contribute to reduce nutrient pollution if the application is efficient (i.e., nutrient leaching to

- The costs of water reuse are sufficiently low to enable a sustainable operation of the reuse system;
- The benefits to agricultural production brought by reused water are sufficiently high;
- Climate change and competing water uses threaten the region in terms of reduced water availability.

The occurrence of these conditions may be checked by calculating specific indicators, one for each criterion (Table 5).

For nutrient pollution, we build indicators based on the GREEN model developed at the JRC for the purpose of assessing annual loads of total nitrogen and total phosphorus transported through European rivers (Bouraoui et al., 2011; Grizzetti et al., 2012). The results of the GREEN model were subject to quality checks and by comparison with other models estimations (Grizzetti et al. 2015; Malago et al. 2015). Here we refer to the GREEN model setup discussed in Pistocchi et al., 2018. The distribution of nitrogen concentrations in Europe, predicted by the GREEN model, is shown in **Figure 33**. GREEN is also applied to estimate the ratio of local point source emissions (tonnes/year) to the load coming from the catchment upstream, for each European sub-basins. This ratio is shown in **Figure 34**. In this assessment we use, as an indicator of potential benefits in terms of nutrient pollution control associated with water reuse, the percent of sub-basins with point source N emissions in a NUTS2 region where point sources represent at least 40% of the N load conveyed from the upstream river basin, *and* estimated concentrations in rivers equal or exceed 8 mg/L of N (**Figure 35**).

Table 5. Indicators for the reuse priority criteria considered in this assessment.

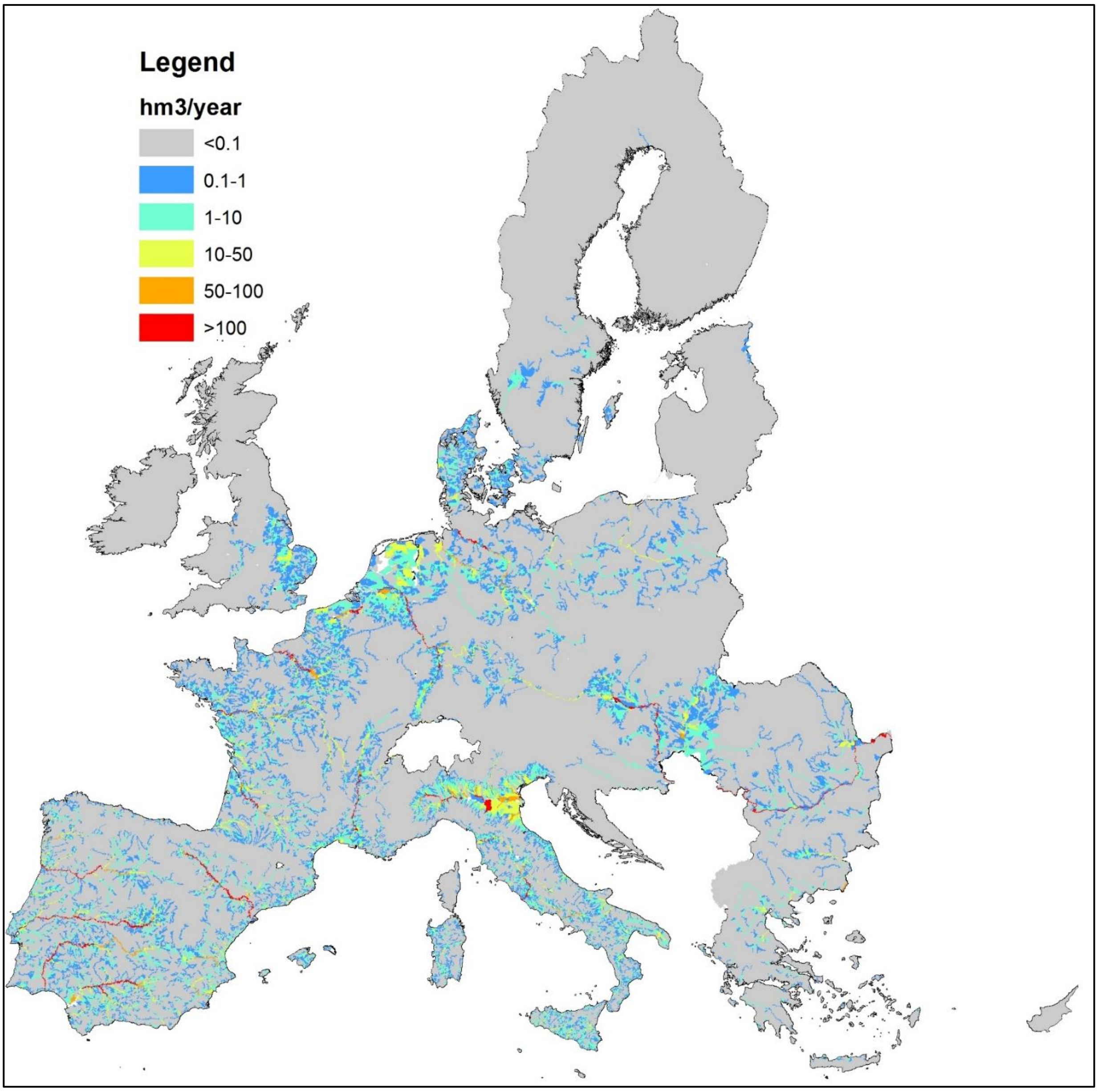
Criterion	**Indicator**
Costs of reuse	Average total cost per m^3 of reused water at NUTS2 level
Water stress reduction	Average contribution of reuse to reduction of water appropriation (weighted by stream discharge)
Climate change threats	Average reduction of water availability by NUTS2 region (weighted by stream discharge) as the median of RCP 8.5 scenarios
Nutrient pollution	% of sub-basins in the NUTS2 region with presence of point sources, where impact criteria are met
Benefits to agricultural production	Average crop market value by NUTS2 region

Source: JRC

Costs are derived directly from the hydroeconomic assessment presented in Pistocchi et al., 2017. The benefits brought by water reuse in terms of agricultural production are estimated as explained in section 9 of Pistocchi et al., 2017, and aggregated by level 2 NUTS region in **Figure 36**. The indicators of water stress mitigation potential and impacts of climate change are shown in **Figure 8** and **Figure 30**.

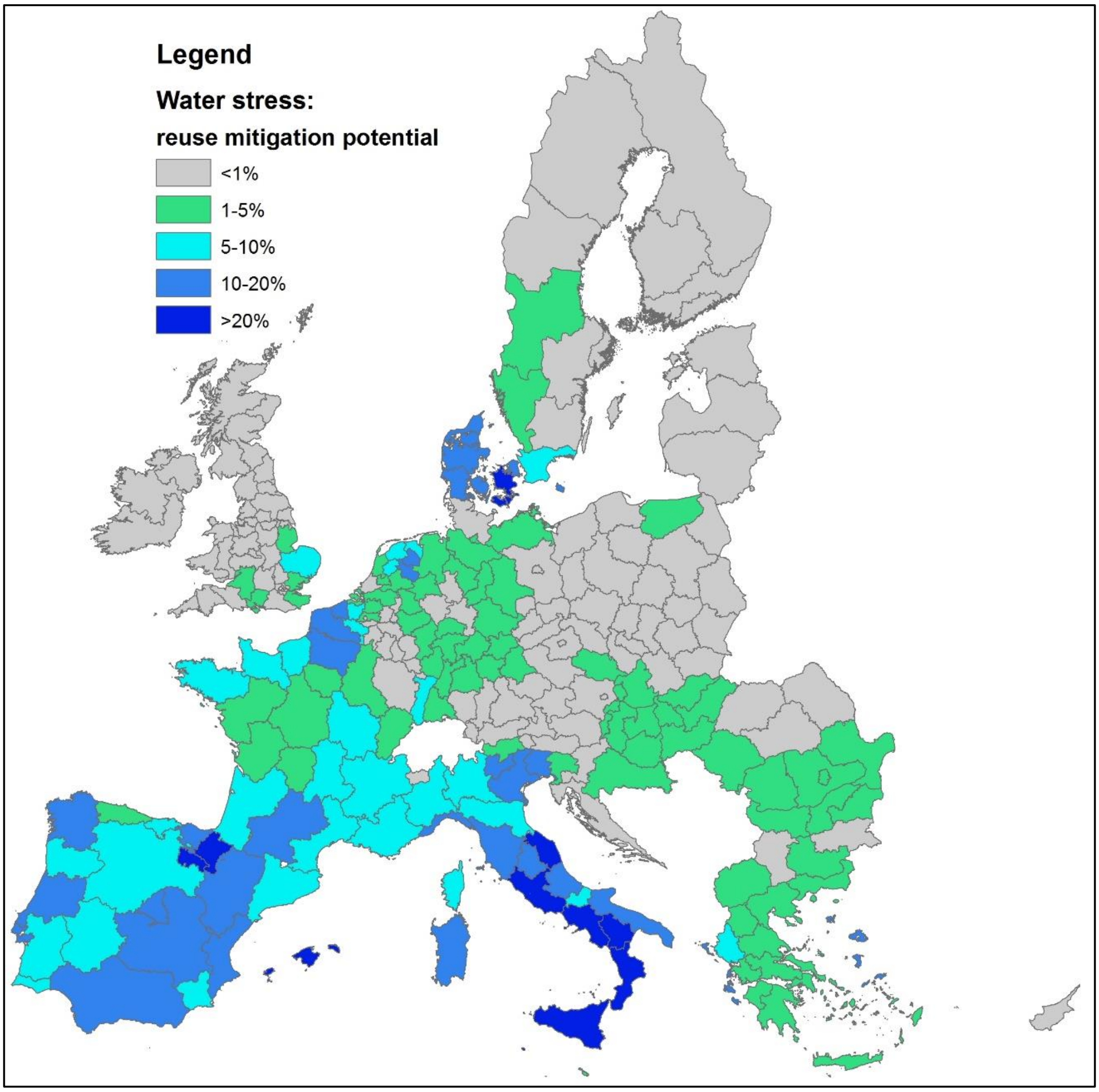
groundwater is not increased) and the mineral fertilizers used in agriculture are reduced proportionally to the nutrient flows coming with reclaimed water. *Coeteris paribus*, and provided that fertirrigation is efficient, water reuse may be more useful where the discharge of WWTPs (point source) represents a significant share of the load conveyed by the river, and the nutrient concentration in the river is relatively high.

Figure 29. Cumulative reclaimed water that can be allocated for irrigation in European river basins, assuming no cost restriction



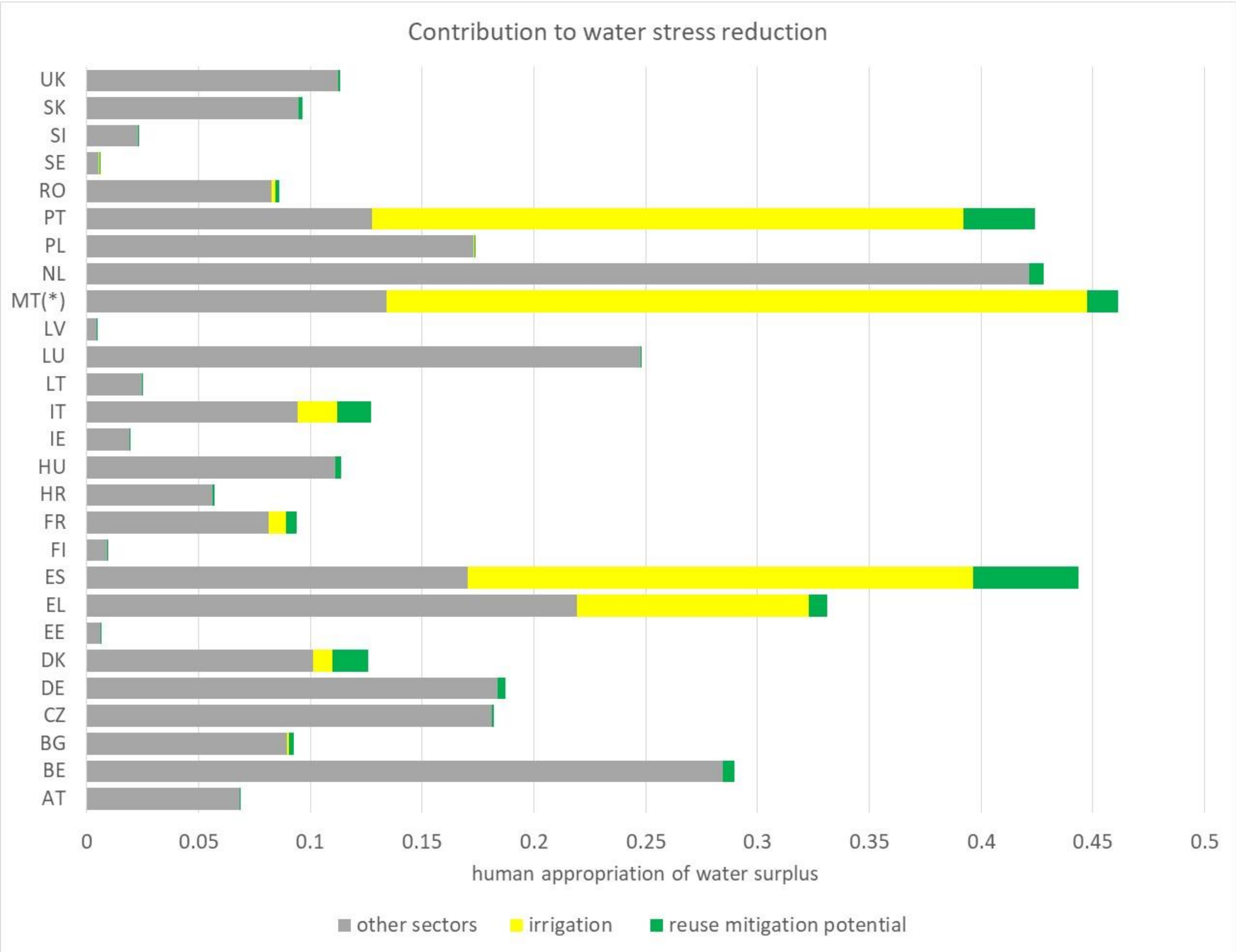
Source: JRC

Figure 30. Reuse mitigation potential by NUTS2 region



Source: JRC

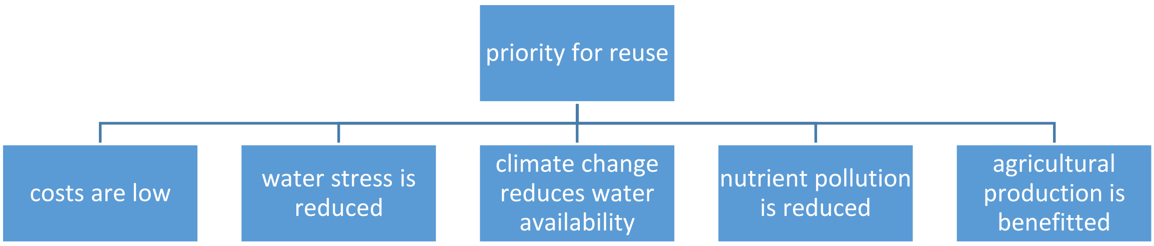
Figure 31. Country-level summary of the contributions to water stress reduction. The value axis represents the appropriation indicator (**Equation 8**), highlighting the share of it owing to irrigation and the share that could be avoided with water reuse



(*) For Malta (MT) the figures were rescaled for readability reasons and must be multiplied by 5.

Source: JRC

Figure 32. Decision tree for the prioritization of water reuse



Source: JRC

The indicators must be normalized in order to be comparable. First, for each indicator we rank the level-2 NUTS regions of Europe consistently, so that a region for which an indicator suggests higher priority receives a rank number closer to 1. The rank number is then used to compute the normalized indicator as follows:

Equation 14. Normalization of priority indicators

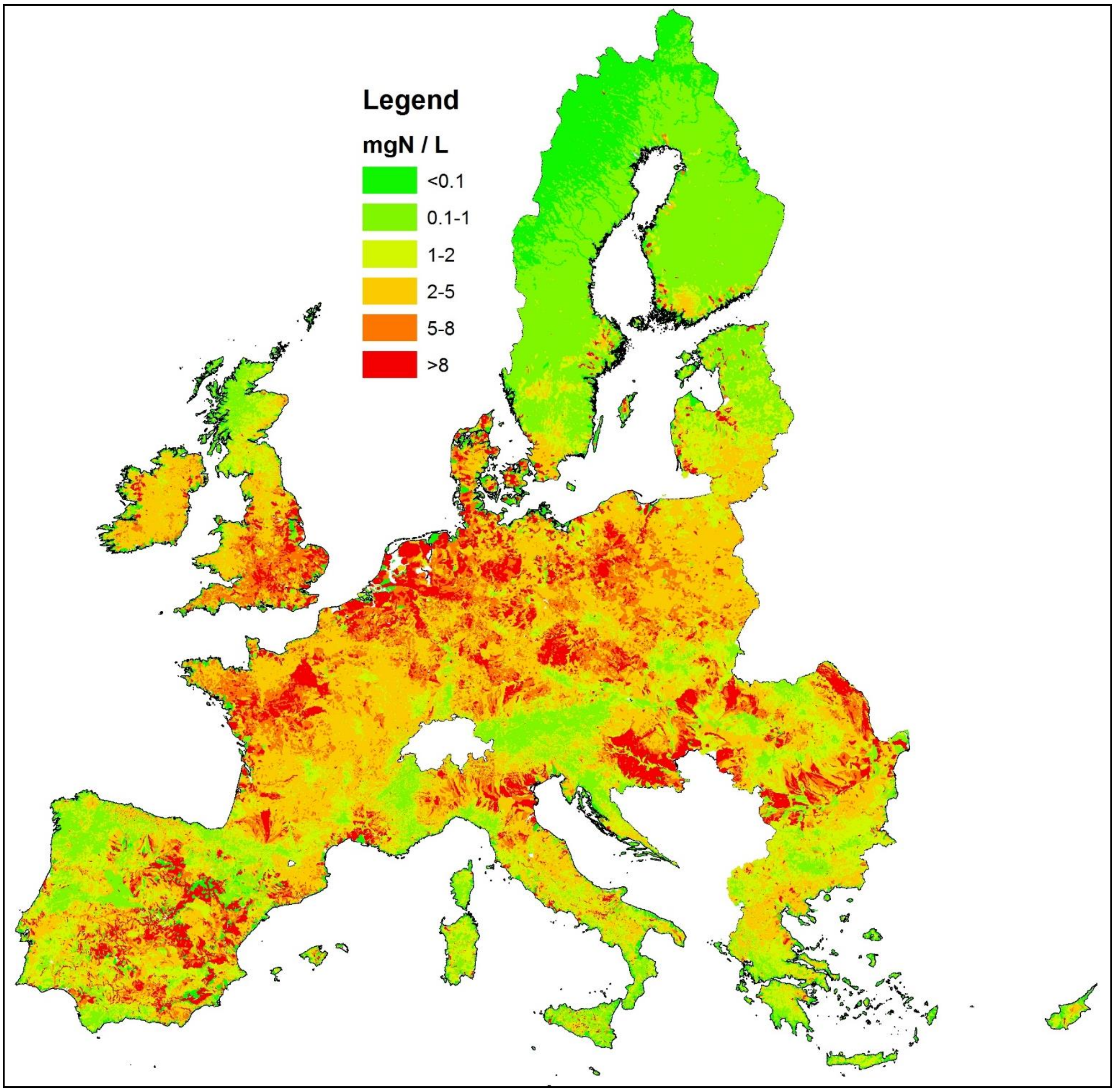
$$I_{i,j} = 1 - \frac{RN_{ij}}{N}$$

where $I_{i,j}$ is the normalized indicator for criterion j (**Table 5**) assigned to region i; RN_{ij} is the rank number assigned to region i for criterion j, and N is the number of NUTS2 regions in the ranking. All regions classified with the maximum rank number for criterion j are finally assigned $I_{i,j}$ =0. $I_{i,j}$ takes values between 0 and 1, with 1 indicating NUTS2 regions with highest priority for water reuse according to criterion j. This method is simple and aims merely at visualizing the relative ranking position of regions for each criterion. Figure 37 shows the maps of the individual normalized indicators for all NUTS2 regions.

The indicators of priority for individual criteria can be summed together in order to visualize those regions where more than one criterion indicates a high priority. For the sake of visualization, we plot the sum of the normalized indicators (ranging between 0 and 5, for regions where no criterion or all criteria are met, respectively) for the EU's NUTS2 regions in the graphs of Figure 54 to Figure 64 of Annex 3.

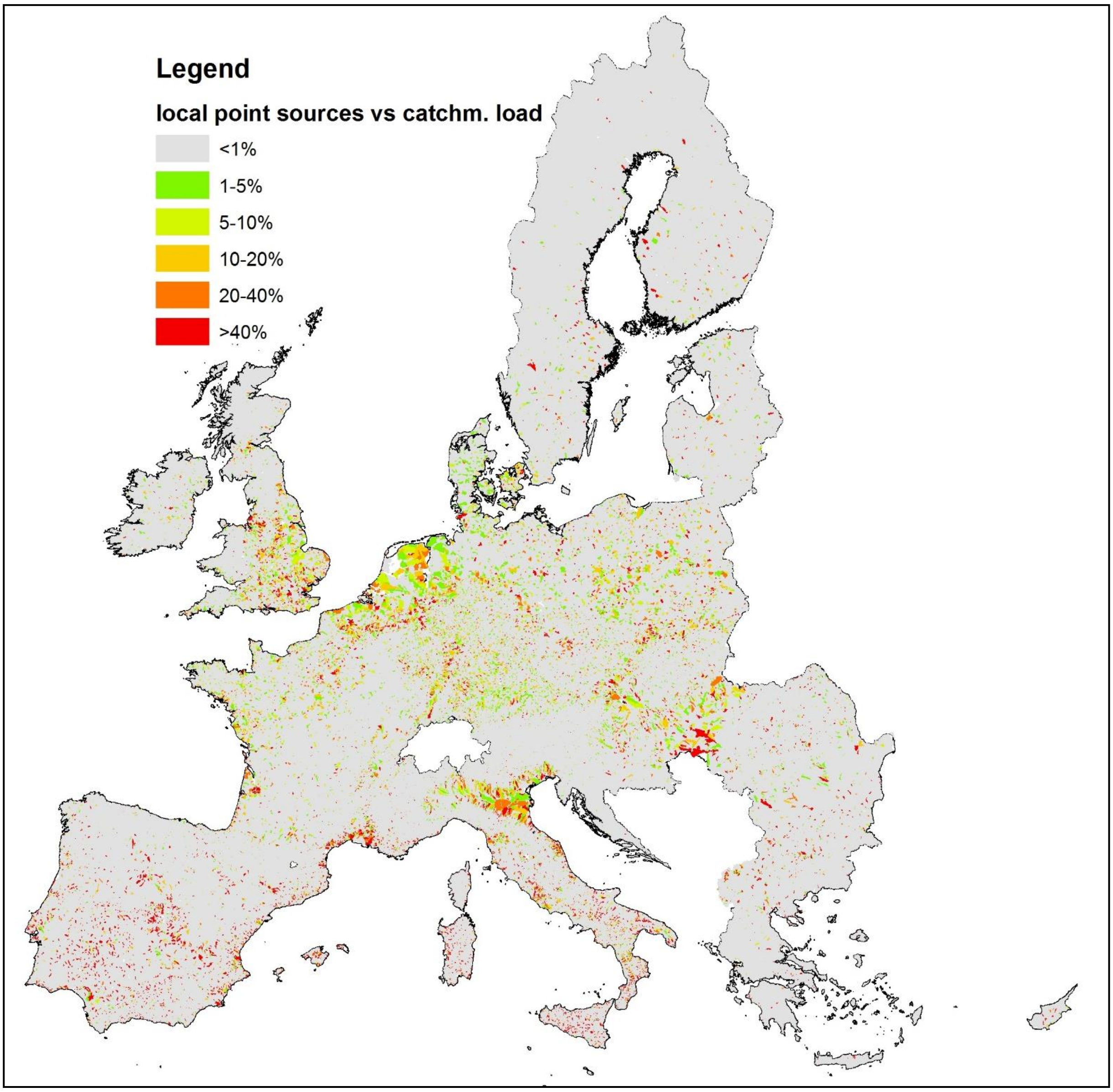
From an inspection of the maps, it emerges that Southern Europe is generally more favourable for reuse under most criteria, although with a certain variability. Other parts of Europe, e.g. in Belgium, the Netherlands and Denmark, feature relatively high favourability except for the criterion of climate change threats, as the Budyko model does not predict a decrease in water availability. Northern and Central Europe generally feature lower favorability for all criteria. France and parts of Spain and Italy show high favorability only for some of the 5 criteria considered in this assessment.

Figure 33. Concentration of nitrogen in European streams, as predicted by the GREEN model.



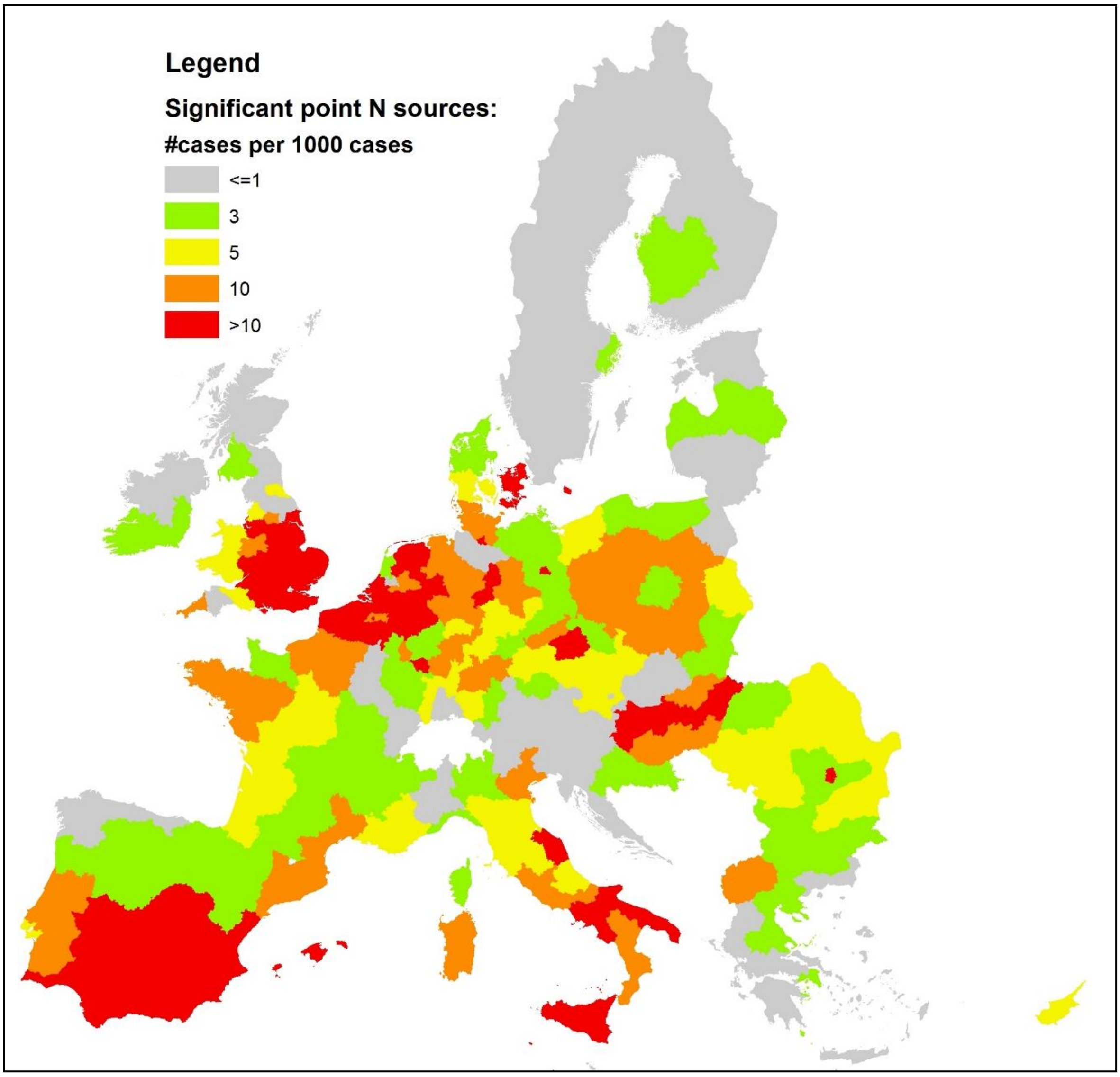
Source: JRC

Figure 34. Local point source emissions as a fraction of the nitrogen loads coming from the catchment upstream, from the GREEN model.



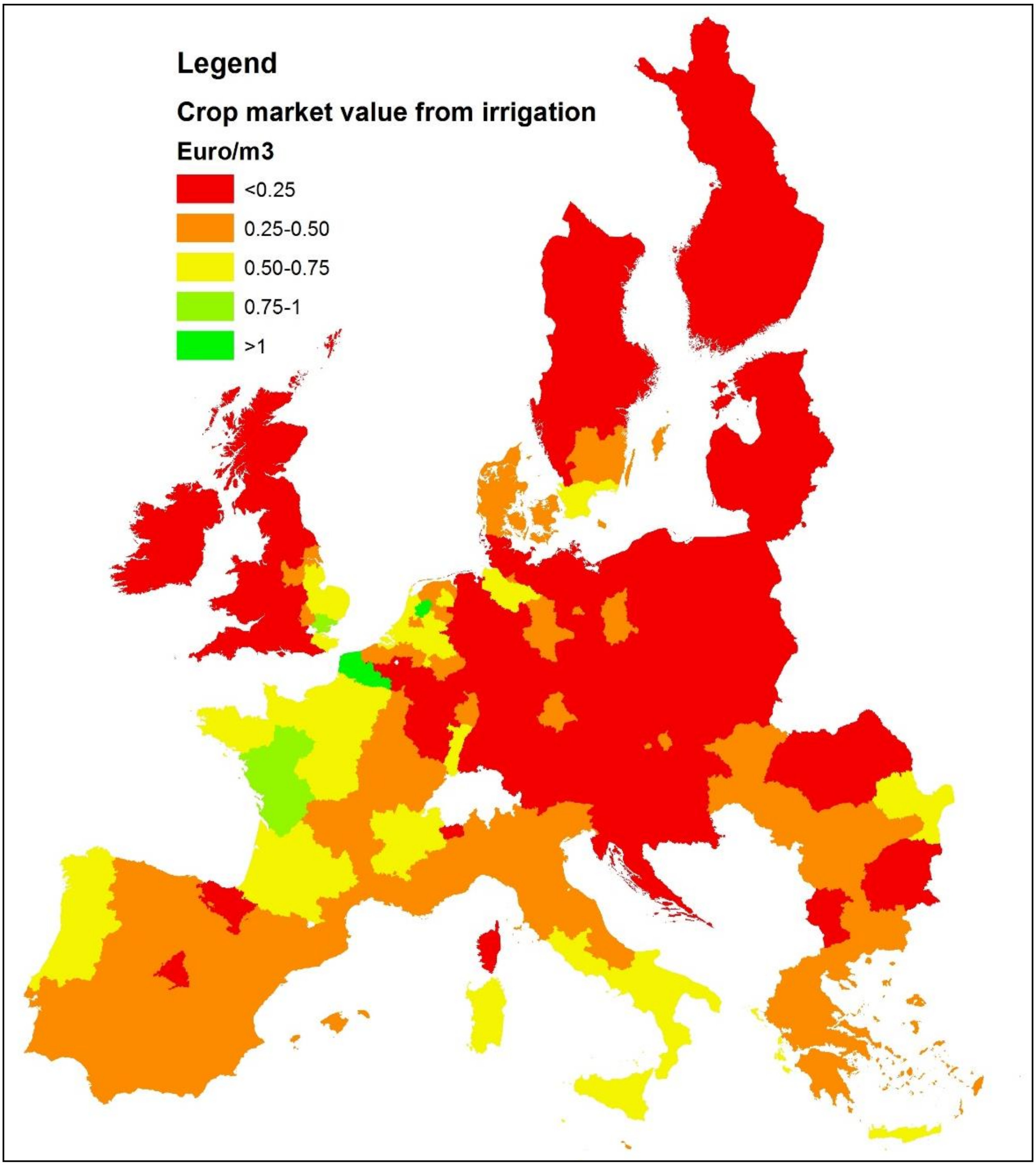
Source: JRC

Figure 35. Indicator of potential benefits in terms of nutrient pollution control associated with water reuse.



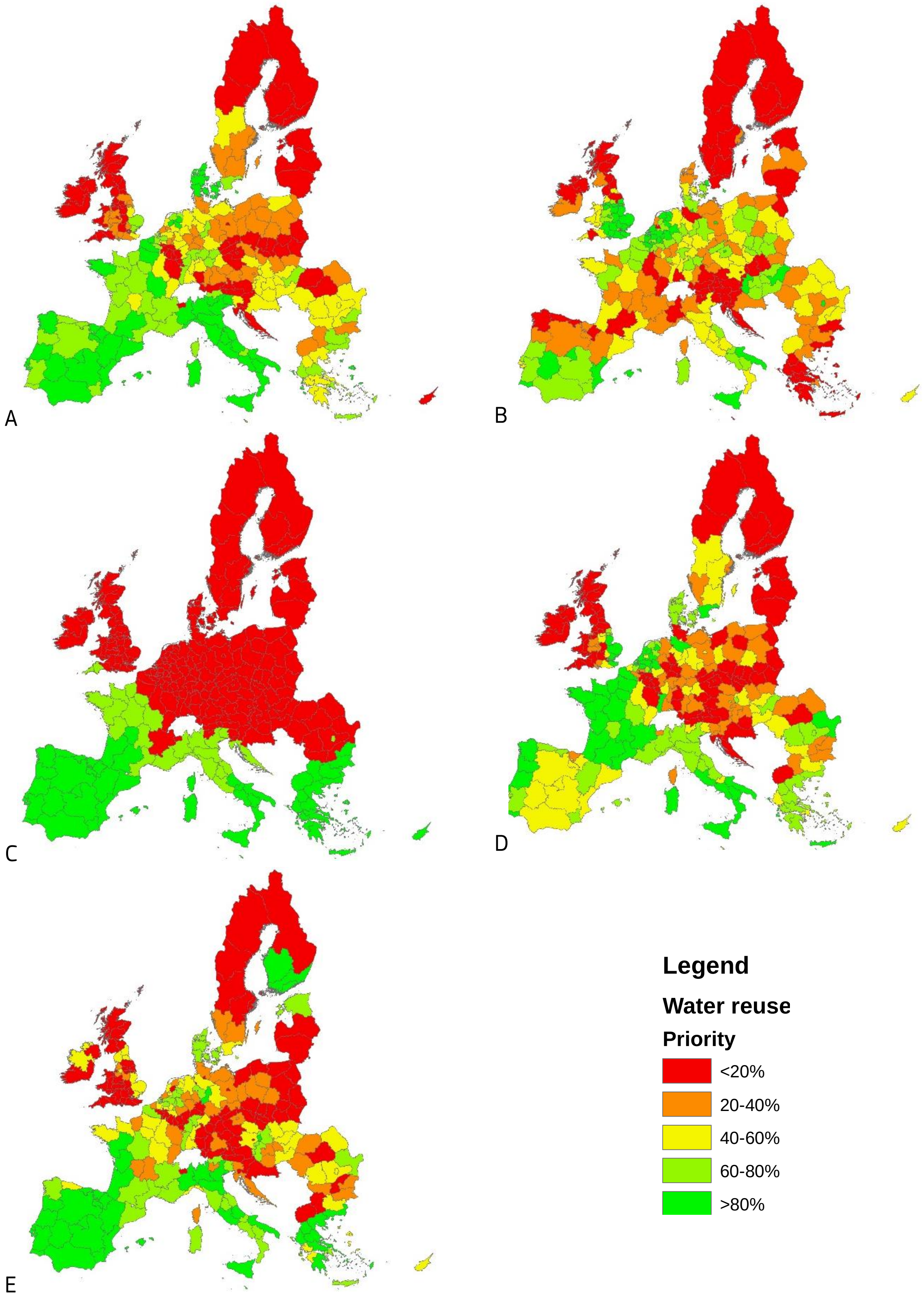
Source: JRC

Figure 36. Aggregation by NUTS2 regions of the value of additional crop production per m^3 of irrigation water from Pistocchi et al., 2017,



Source: JRC

Figure 37. Maps of normalized indicators used to prioritize water reuse: (A) water stress reduction; (B) nutrient pollution reduction; (C) climate change; (D) crop market value; (E) water reuse costs. Indicators as normalized as per **Equation 14** are expressed as a percentage instead of a fraction.



Source: JRC

6 Conclusions and way forward

We have presented an analysis of water appropriation in Europe, based on estimated demand in key economic sectors and estimated volumes of water available using a simple model.

The availability side of the water balance is relatively well represented, particularly when aiming at time-aggregated and European-scale comparisons among policy and other scenarios. The simple Budyko framework-based model used to quantify water availability has proven to provide a reasonable proxy to more accurate estimates delivered by the LISFLOOD model. The latter is used operationally in the European Flood Awareness System (EFAS) as well as in the European Drought Observatory (EDO), and its calibrated reference run is the primary source for the reconstruction of historic streamflow time series. However, the proxy model is inexpensive and can be quickly applied to appraise scenarios, particularly when in need to consider complex ensembles of climate models often raising severe computational demands.

Less robust is instead the representation of the demand side of the water balance. We have shown that the volume of water demand for domestic (public) water supply, industry, energy production (cooling), livestock and irrigation can be estimated with varying consistency from different information sources (**Figure 14** to **Figure 17**). However, knowledge gaps still exist which must be filled in order to achieve a full understanding of the balance between availability and demand, and the prioritization of investments for water resilience in Europe. While domestic water use is relatively well known, water use for energy and, even more, livestock, irrigation and industry require further study. The EEA is already developing accounts of water abstractions in Europe, bringing together Eurostat data and more detailed information from Member States, and applying machine learning to fill the gaps. This approach is arguably the best available option to achieve representative input for European water balance calculations, and should be better streamlined with modelling activities including with LISFLOOD.

Water demand could be quantified with a bottom-up approach, i.e. considering the distribution in time and space of water-using activities and appropriate “water use factors” as used e.g. in environmental (water) footprinting exercises. On this line, we have already shown the results from the JRC PPDB and its update in the context of the EIGL. A bottom-up estimation has been proposed here also for livestock water requirements using livestock population statistics, regularly collected by Eurostat, through relatively well established water use factors.

Reconciling water abstraction data (e.g. from Eurostat) with bottom-up estimates could help shed light on the actual distribution of water use, also considering that the location and type of European industrial facilities is known in fine detail[24].

For irrigation, the available data deserve additional scrutiny, in particular in order to check whether the irrigated areas are captured correctly. Areas of irrigation can be related to the distribution of crops, whose extent statistics are quite comprehensive for Europe.

Crop water requirements reflect the weather during the crop growth season, and may be fairly well modelled within LISFLOOD or, more accurately, with agro-hydrological models such as EPIC presently incorporated in a research version of the LISFLOOD model (Gelati et al., 2020). Combining

[24] https://industry.eea.europa.eu/

modelled crop water requirements with a map of irrigation areas may deliver a bottom-up estimation of irrigation demand to compare with, and to fill the gaps of available statistics.

Bottom-up estimates are essential not only to fill gaps, but also to understand how to better manage existing demands and how to achieve water efficiency objectives as set out in the Water Resilience Strategy and the related “Efficiency first” recommendation[25].

Assessing specific and emerging water demands requires solid aggregated demand quantification. Data centres, semiconductor production plants, hydrogen production plants, the food and beverage and process industry and other emerging industrial water users may come to stage in the coming few years, and need to be appraised specifically beyond a sector-aggregated water balance. As an example, a socio-economic study recently published by Water Europe[26] calculates a water requirement for the production of cheese in the EU in excess of 50 billion m^3/year. While the study does not specify which share of this volume is “green water” of feed crops for cattle and sheep/goat (hence already accounted for with irrigation, or even “green water” coming directly from precipitation), a plausible share of 10% (i.e. more than 5 billion m^3/year) could correspond to “blue water” needed by the industry (including for process and cooling), see e.g. Grossi et al., 2024. On the same line, beer production is estimated to require 1.7 billion m^3/year, although only a small share of this owes to process water in the industry and the rest is related to irrigation of crops[23].

The semiconductors industry presently requires ca. 0.5 billion m^3/year of water and could almost double this requirement by 2030[23]. The EU data centres could require just under 0.1 billion m^3/year by 2030, and electric vehicle battery production a similar amount[23]. These sectors combined could already account for a few percentage points of the current envelope of EU water abstractions (or demand).

The objective of 10 million tonnes of hydrogen produced yearly in the EU by 2030, on top of 10 million tonnes imported[27] entails use of 0.4 billion m^3/year assuming a water requirement of 20 m^3/ton H_2 (20 liters per kg of hydrogen). This corresponds to the domestic demand of approximately 5 to 6 million people, an amount that does not affect the water balance significantly at EU level, but can have substantial impacts if concentrated in few regions. To put emerging or specific sectorial demands in perspective, it is all the more important to dispose of a solid quantification of aggregated water demand.

All economic sectors may represent important water users, with large regional variations. At European scale, all our knowledge sources indicate that the largest demand is from the energy sector (**Figure 19**), followed by irrigation, although the ranking varies substantially from region to region. Most European regions do not feature a largely dominant water-using sector, as highlighted by Kwoka’s dominance index (**Figure 13**). This suggests that water management could very often focus on finding synergies and trade-offs among various users.

Between 10 and 50% of the naturally available water volumes are appropriated for human activities (Figure 20). A few, water-richer and less densely inhabited regions have lower

[25] https://environment.ec.europa.eu/publications/commission-recommendation-water-efficiency-first-guiding-principles_en

[26] https://watereurope.eu/wp-content/uploads/2024/10/Water-Europe_Final-Report_15102024-1.pdf

[27] https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en

levels of appropriation, while regions in more arid climates in the South of Europe may even exceed an appropriation of 50%. Irrigation demand represents by far the most appropriative one. Irrigation is also the sector explaining the highest proportion of variance of total potential appropriation in Europe, and is projected to suffer from climate change more than the other sectors (**Figure 24**, **Figure 25**). Livestock water demand is spatially correlated to irrigation demand, and is therefore projected to suffer from similar issues although to a less dramatic extent. This all suggests that the water-food nexus (encompassing the relation between water appropriation and crop or livestock production) is problematic and is going to be increasingly critical for Europe.

Water appropriation could be mitigated through systematic water reuse across sectors. Our screening of the spatial relationships between sectorial demands highlights many cases where there is an opportunity to reuse water across sectors. Reuse of reclaimed domestic wastewater for irrigation is already in the focus of a specific European regulation[28] and could reduce appropriation by 5% to 20% under current conditions (**Figure 30**). However, the projected changes in water availability due to climatic trends require appropriate strategies to reduce their water requirements, including through crop adaptation. While recent policy developments, including the recast Urban Wastewater Treatment Directive (UWWTD) 2024/3019/EU, support more widespread reuse of water for irrigation or industrial use, industrial waters may be more difficult to reuse due to water quality concerns, and need to be assessed specifically. Energy water use is most often less consumptive, and water used for cooling is *de facto* already indirectly available for reuse in many cases.

The distribution in time of available resources may also be of high concern, e.g. if Europe has to face more frequent drought and floods. **We need an understanding of storage requirements** to buffer this variability. This important aspect is not addressed here and should be considered in future studies. Industry and domestic water supply may face challenges particularly in the Southern regions, with high competition for resources.

To date, there is no general agreement on the limits to freshwater abstraction before "planetary boundaries" might be trespassed. This owes to a lack of uncontroversial evidence on the amount of water that needs to be secured for ecosystems. Establishing ecological limits to freshwater appropriation in a given river basin is not a straightforward endeavor (Acreman and Dunbar, 2004). As a matter of fact, we assume that impacts on aquatic systems increase with the level of water appropriation, but we do not aim at defining a quantitative relationship between appropriation and impacts. Still, the percentage of available volume that is appropriated for human activities is so high that its control appears already crucial in order to ensure impacts on aquatic ecosystems are acceptable, also in light of recent assessments of the relevance of freshwater alterations in the planetary boundaries framework (Richardson et al., 2023).

Along with water reuse across sectors, water efficiency and water saving measures remain essential to reduce abstractions not only in agriculture, but also in the energy sector (for example, dry cooling), in domestic (public) water supply (for example, leakage control) and in industrial processes. Implementing the "efficiency first" principle in water use can prove not only effective in minimizing environmental impacts of abstractions, but also in reducing dependence of economic activities on renewable waters vulnerable to climate change and climate extremes, thus supporting overall water resilience in Europe, while also saving on water costs. In order to monitor

[28] Regulation (EU) 2020/741: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0741&from=EN

and manage targets of water use efficiency, an improved water balance remains an essential tool that deserves further development at European scale.

The assessment presented in this study serves as a quick screening of the interplay between demand and availability of water. For assessments in more detail, also addressing the variability in time of both components, it is necessary to use more specific tools such as the LISFLOOD model, embedding a representation of water demand and abstractions in Europe, extensively used for analyses at the continental and regional scales.

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List of abbreviations and definitions

Abbreviations	Definitions
AT	Austria
BE	Belgium
BG	Bulgaria
CY	Cyprus
CZ	Czechia
DE	Germany
DEM	Digital elevation model
DK	Denmark
EDO	European Drought Observatory
EE	Estonia
EEA	European Environmental Agency
EFAS	European Flood Awareness System
EIGL	(JRC) Energy and Industry Geography Lab
EL	Greece
ES	Spain
EU	European Union
FI	Finland
FR	France
HR	Croatia
HU	Hungary
IE	Ireland

Abbreviations	Definitions
IT	Italy
LAEA	Lambert Azimuthal Equal Area
LT	Lithuania
LU	Luxembourg
LV	Latvia
MS	Member State
MT	Malta
NACE	Nomenclature for the statistics of economic activities in the European Community
NL	Netherlands
PL	Poland
PPDB	(JRC) Power Plant Data Base
PT	Portugal
RCP	Representative concentration pathway
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
UWWTD	Urban Wastewater Treatment Directive
WEI	Water exploitation index
WISE	Water Information System for Europe

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Annexes

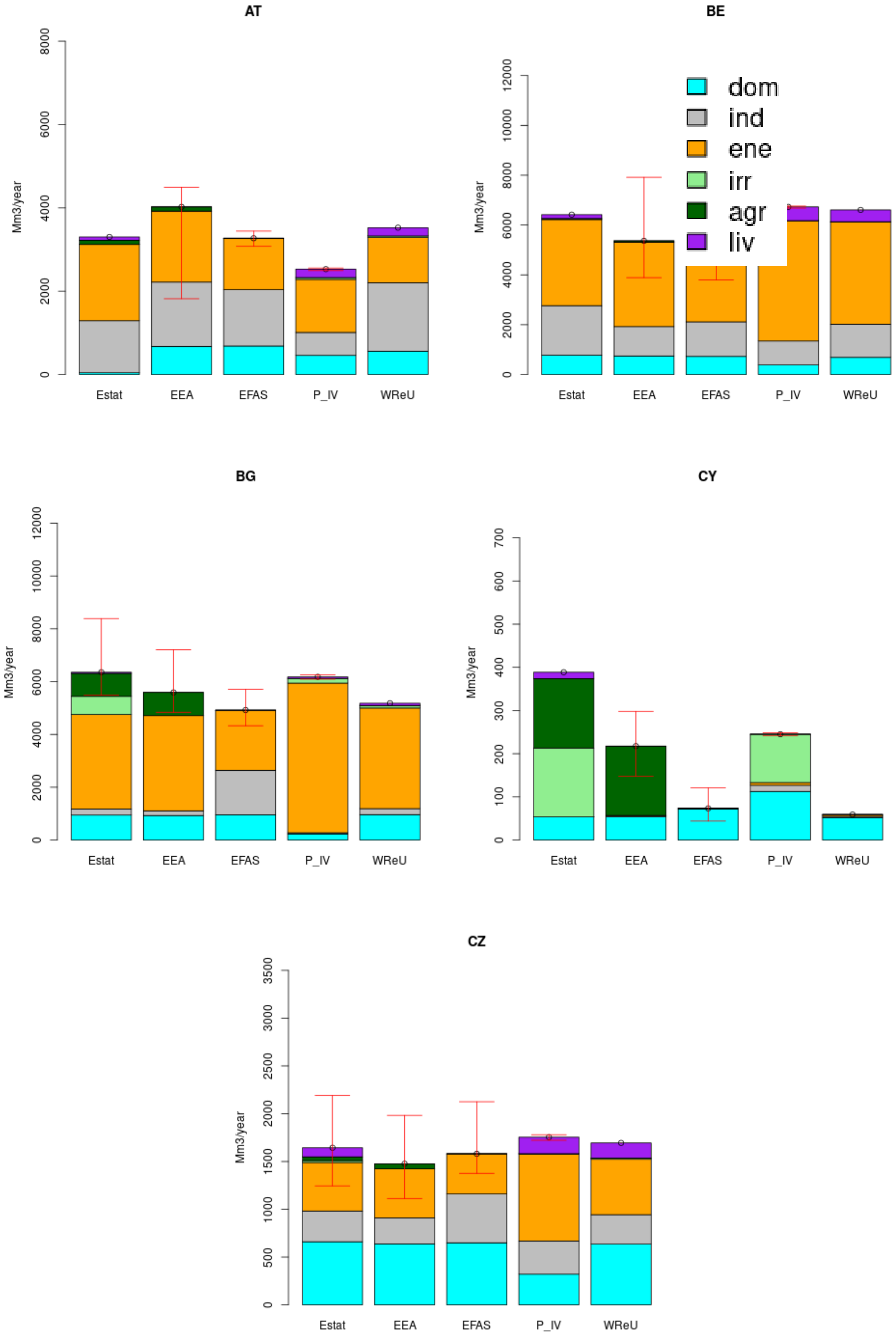
Annex 1– Comparison of different demand estimates for EU Member States

For each of the 27 EU Member States, the following graphs show the median demand for each sector considered here, according to different information sources (as coded in this report), for the period 2000-most recent data. Error bars show the range of estimates of total water demand.

The sectors considered are public (domestic) water supply (dom), livestock (liv), industry (ind), energy (ene) and irrigation (irr).

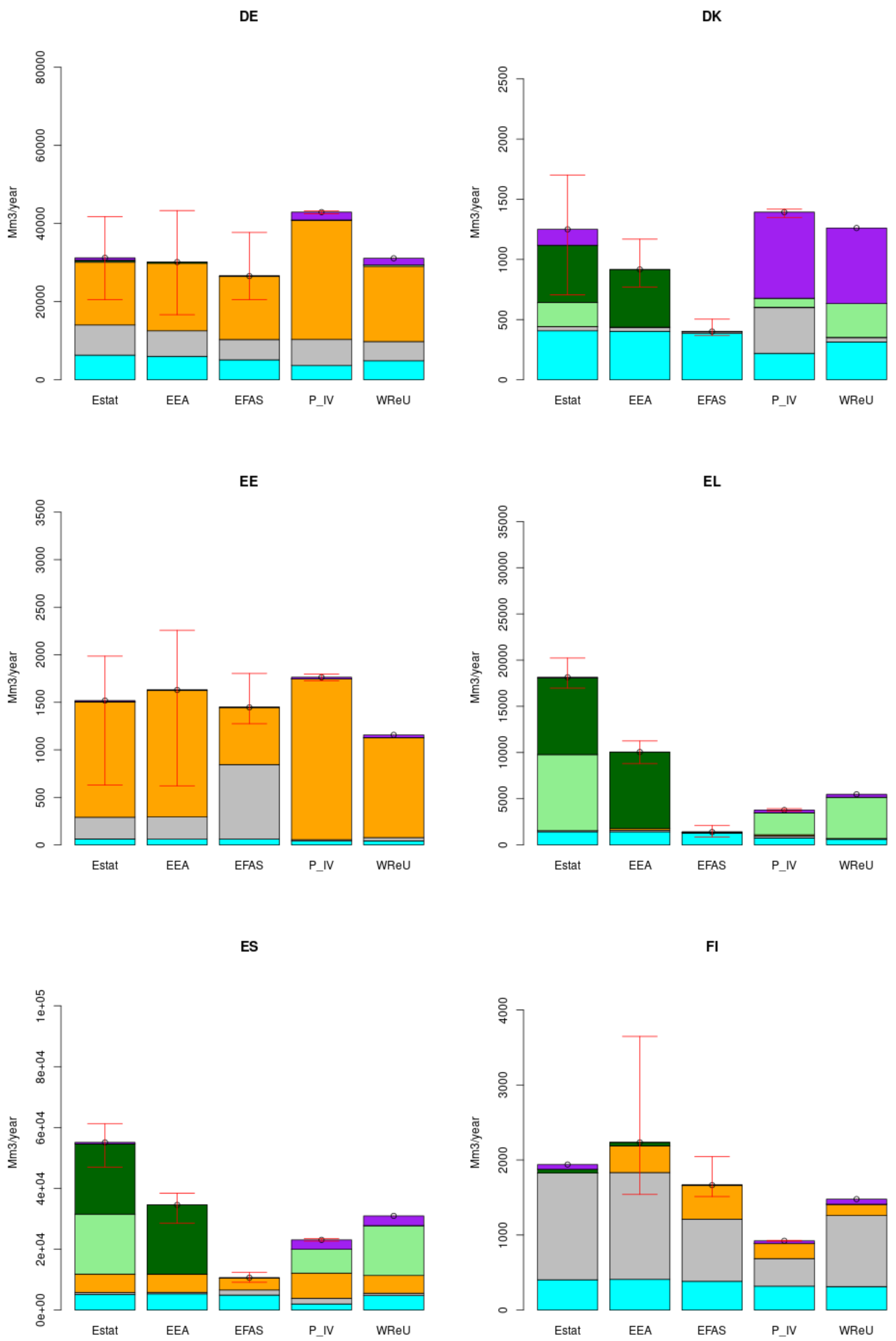
For example, in Austria (AT) all estimates point at water use for cooling as the main demand sector, accounting more than one billion m^3 per year. Industrial water use is the second in rank, just under 1 billion m^3/year. Domestic water use accounts for about half a billion m^3/year while irrigation is much less relevant (<100 million m^3/year). Livestock is between 100 and 200 million m^3/year.

Figure 38 – breakdown of demand for selected countries according to different sources.



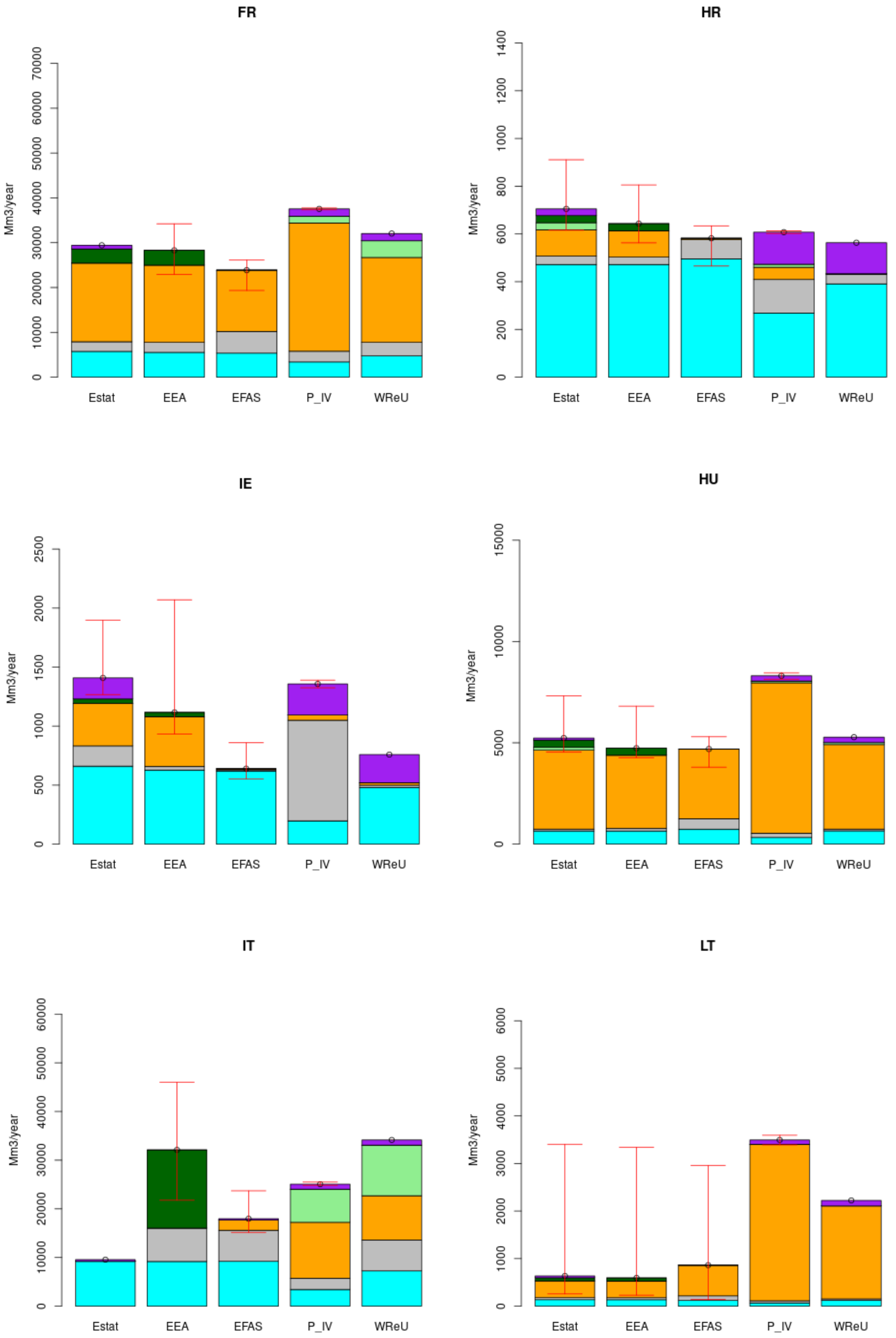
Source: JRC

Figure 39 – breakdown of demand for selected countries according to different sources.



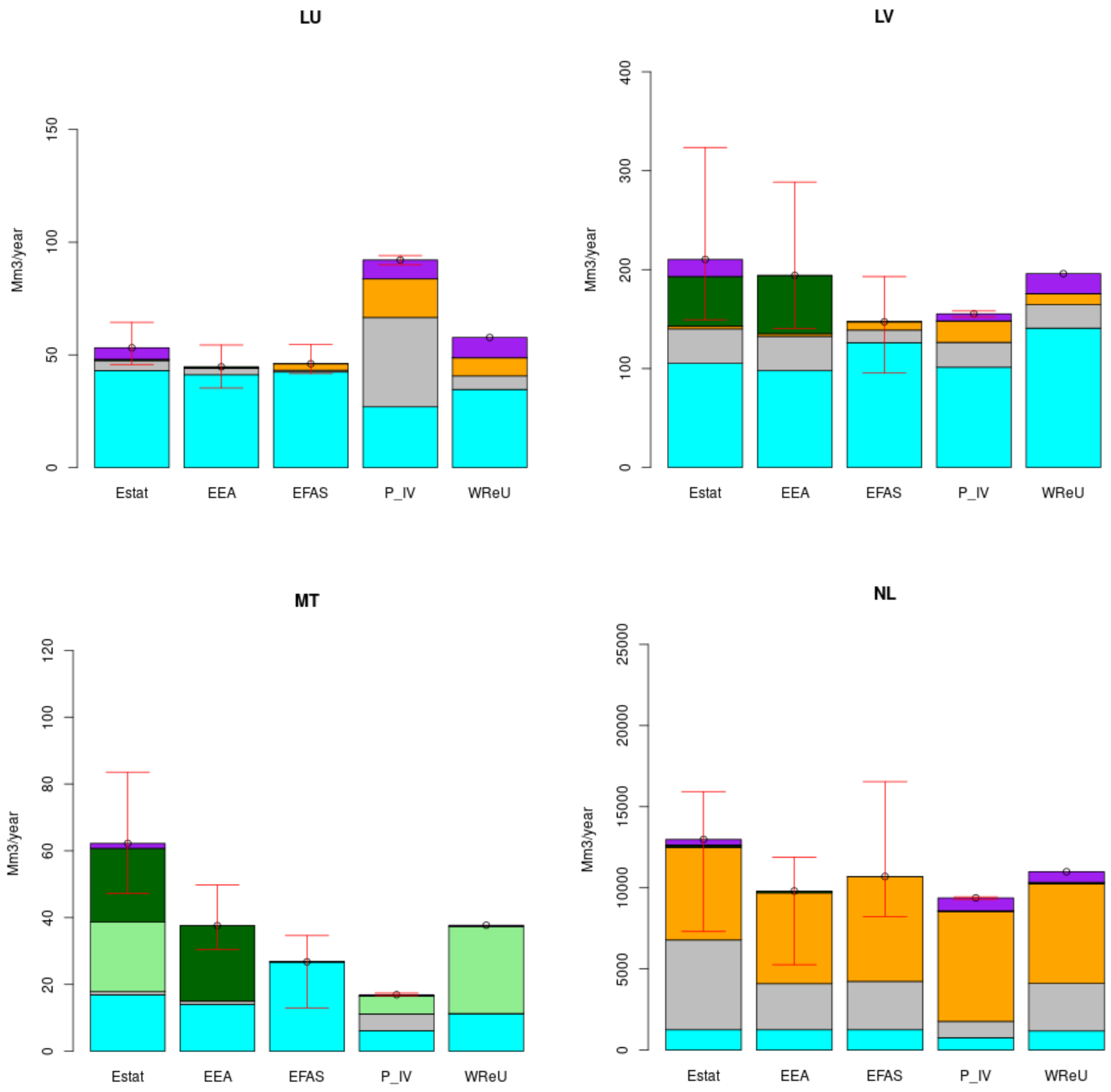
Source: JRC

Figure 40 – breakdown of demand for selected countries according to different sources.



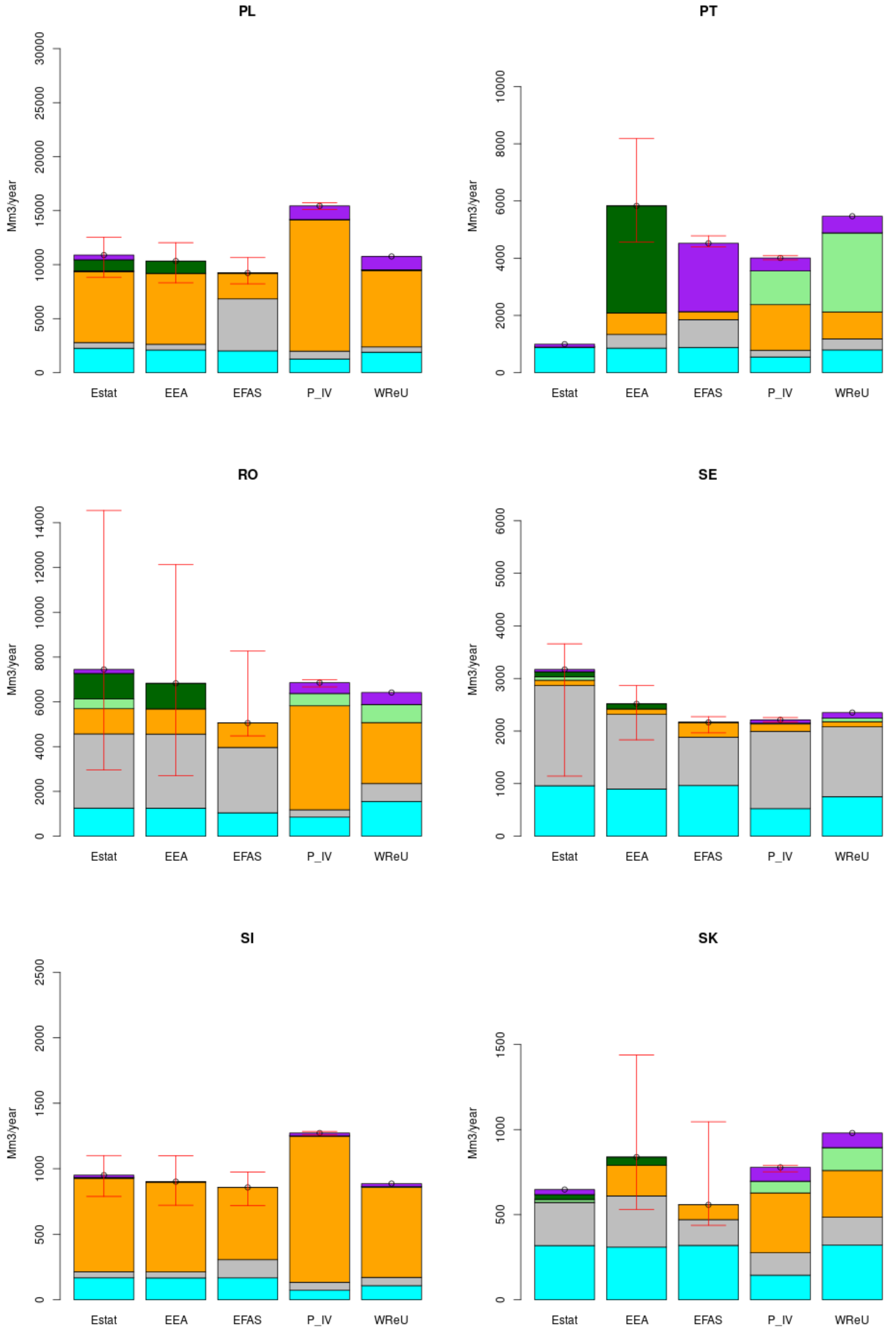
Source: JRC

Figure 41 – breakdown of demand for selected countries according to different sources.


LU
Mm3/year
0
50
100
150
Estat
EEA
EFAS
P_IV
WReU
LV
Mm3/year
0
100
200
300
400
Estat
EEA
EFAS
P_IV
WReU
MT
Mm3/year
0
20
40
60
80
100
120
Estat
EEA
EFAS
P_IV
WReU
NL
Mm3/year
0
5000
10000
15000
20000
25000
Estat
EEA
EFAS
P_IV
WReU

Source: JRC

Figure 42 – breakdown of demand for selected countries according to different sources.

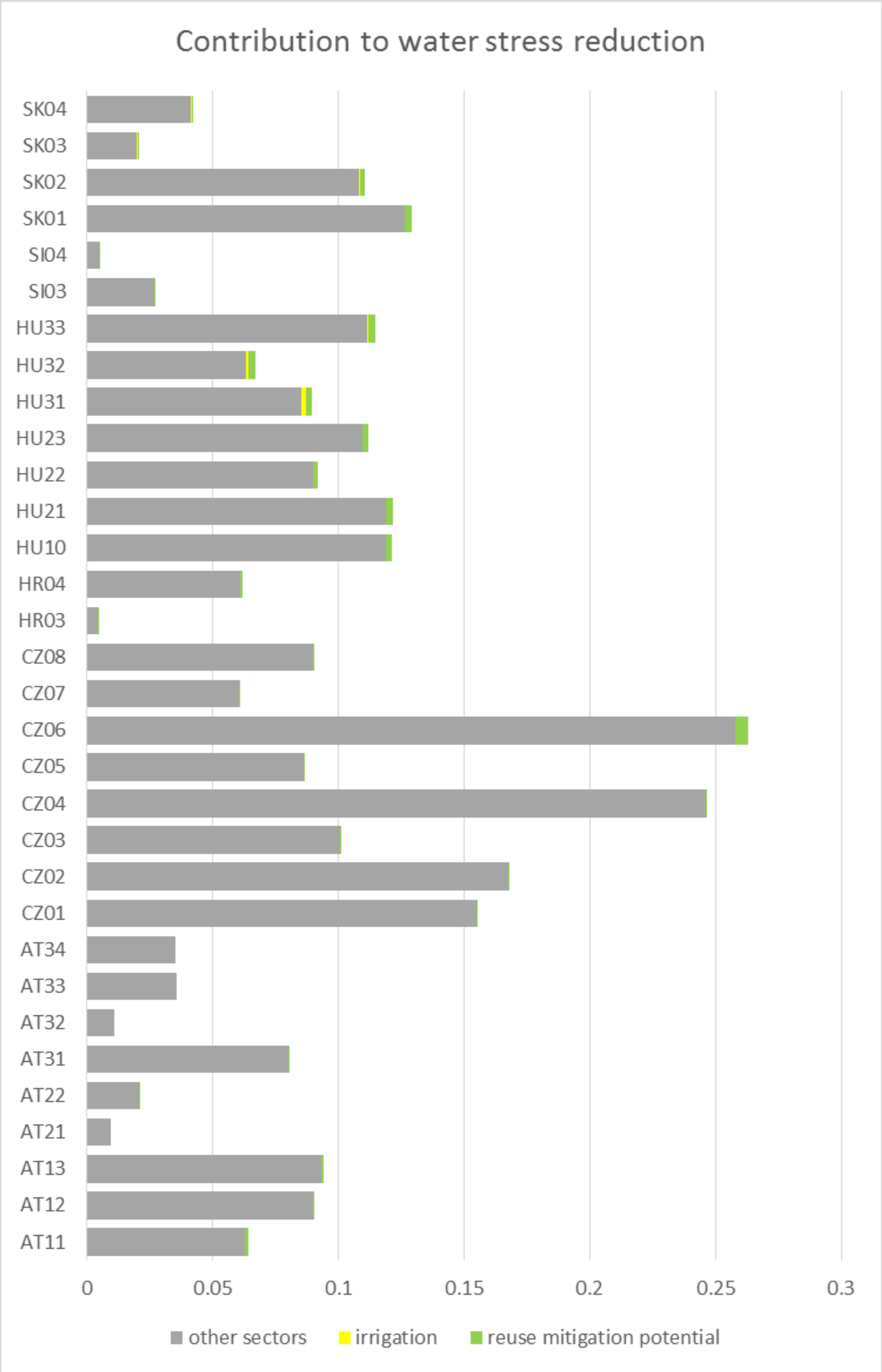


Source: JRC

Annex 2– Potential contribution of reuse to reduce water stress for the NUTS2 regions of the EU

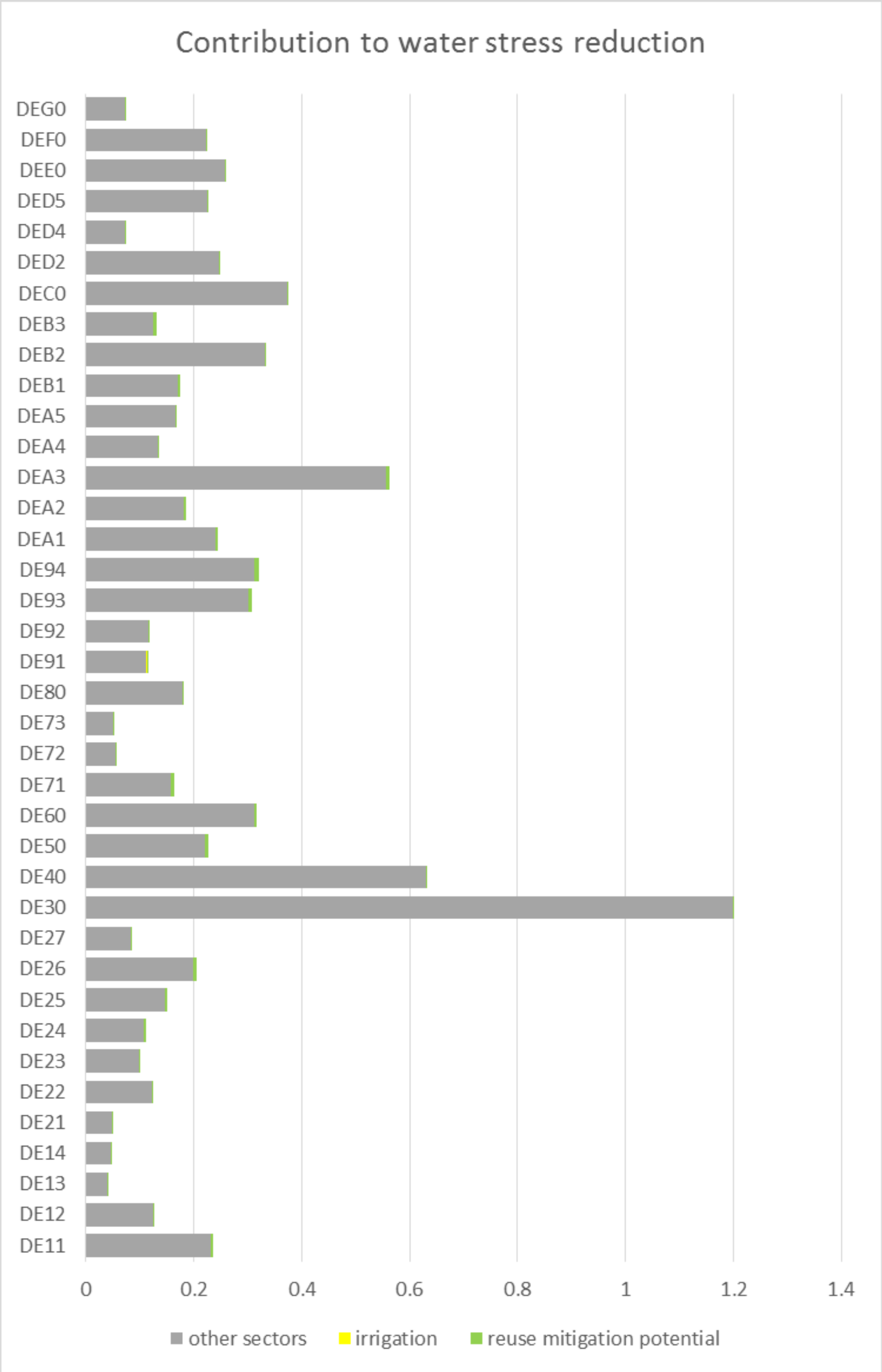
The graphs below visualize, for each level-2 NUTS region in the EU, the contributions to the water appropriation indicator of **Equation 9** from irrigation, from other sectors, and the share of the irrigation contribution that could be mitigated through reuse (assuming no constraints on water reuse costs).

Figure 43 –human appropriation of water surplus, with and without water reuse, under baseline conditions: AT, HU, HR, SI, SK.



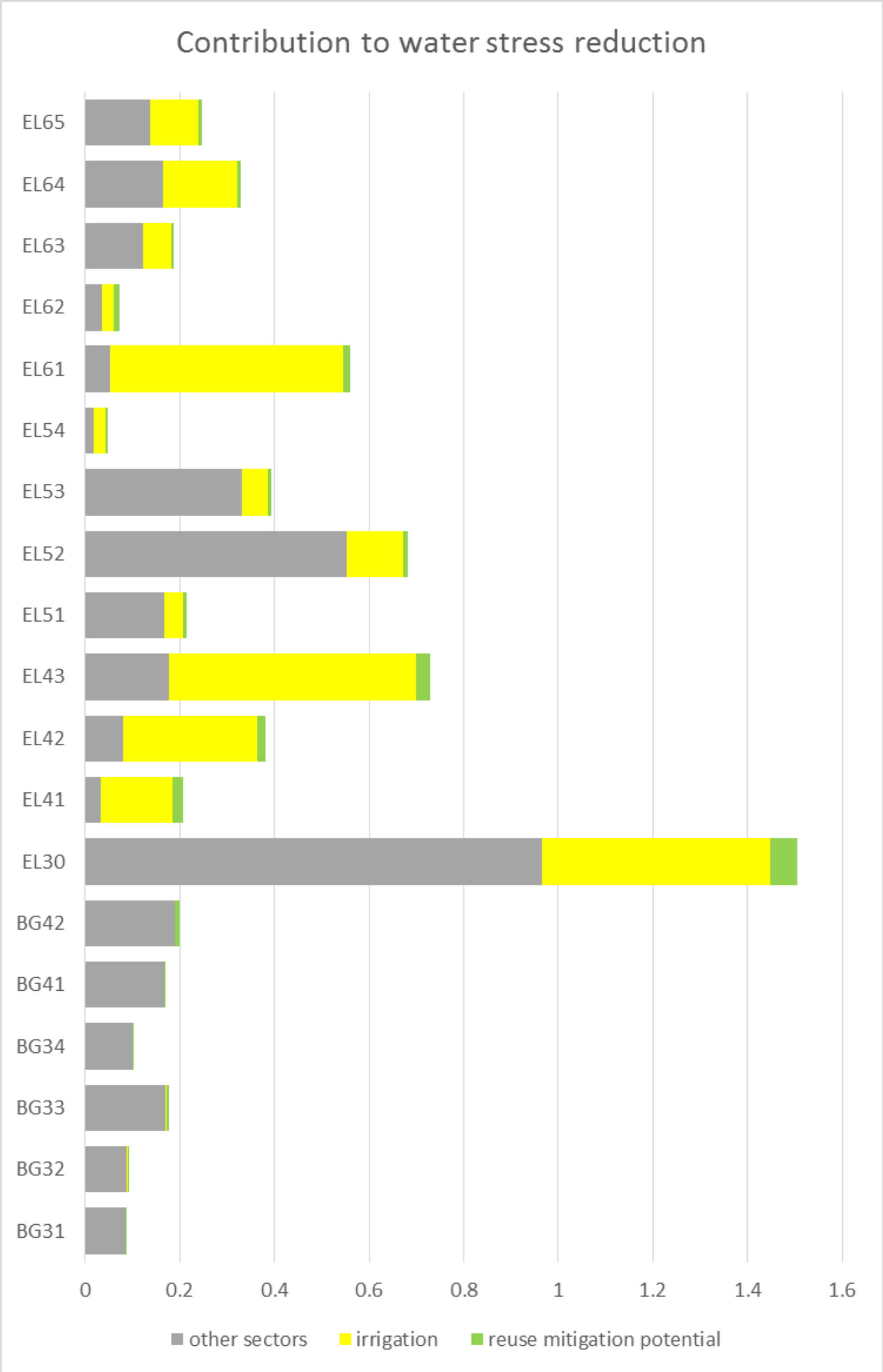
Source: JRC

Figure 44 –human appropriation of water surplus, with and without water reuse, under baseline conditions: DE.



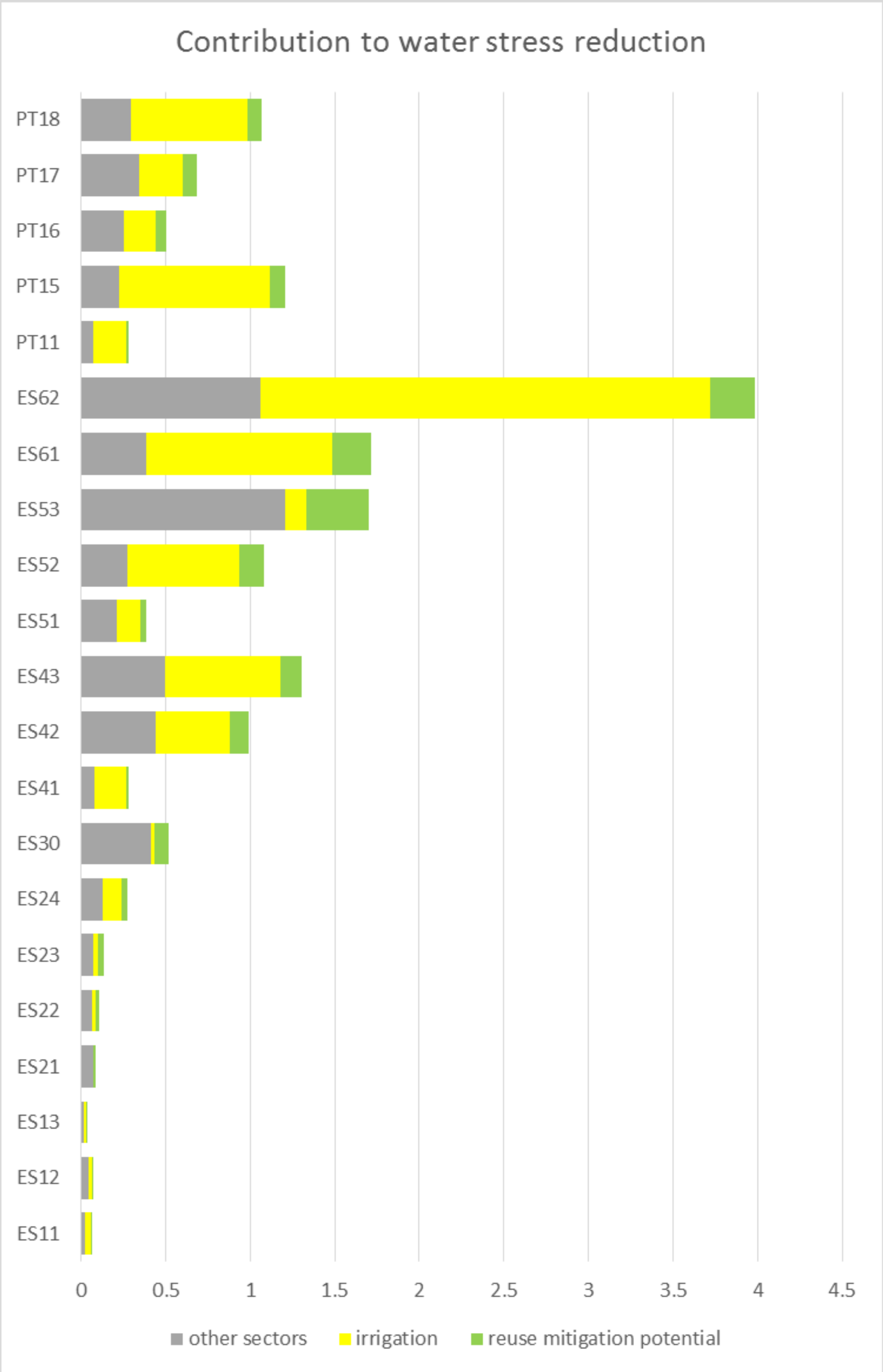
Source: JRC

Figure 45 –human appropriation of water surplus, with and without water reuse, under baseline conditions: EL, BG.



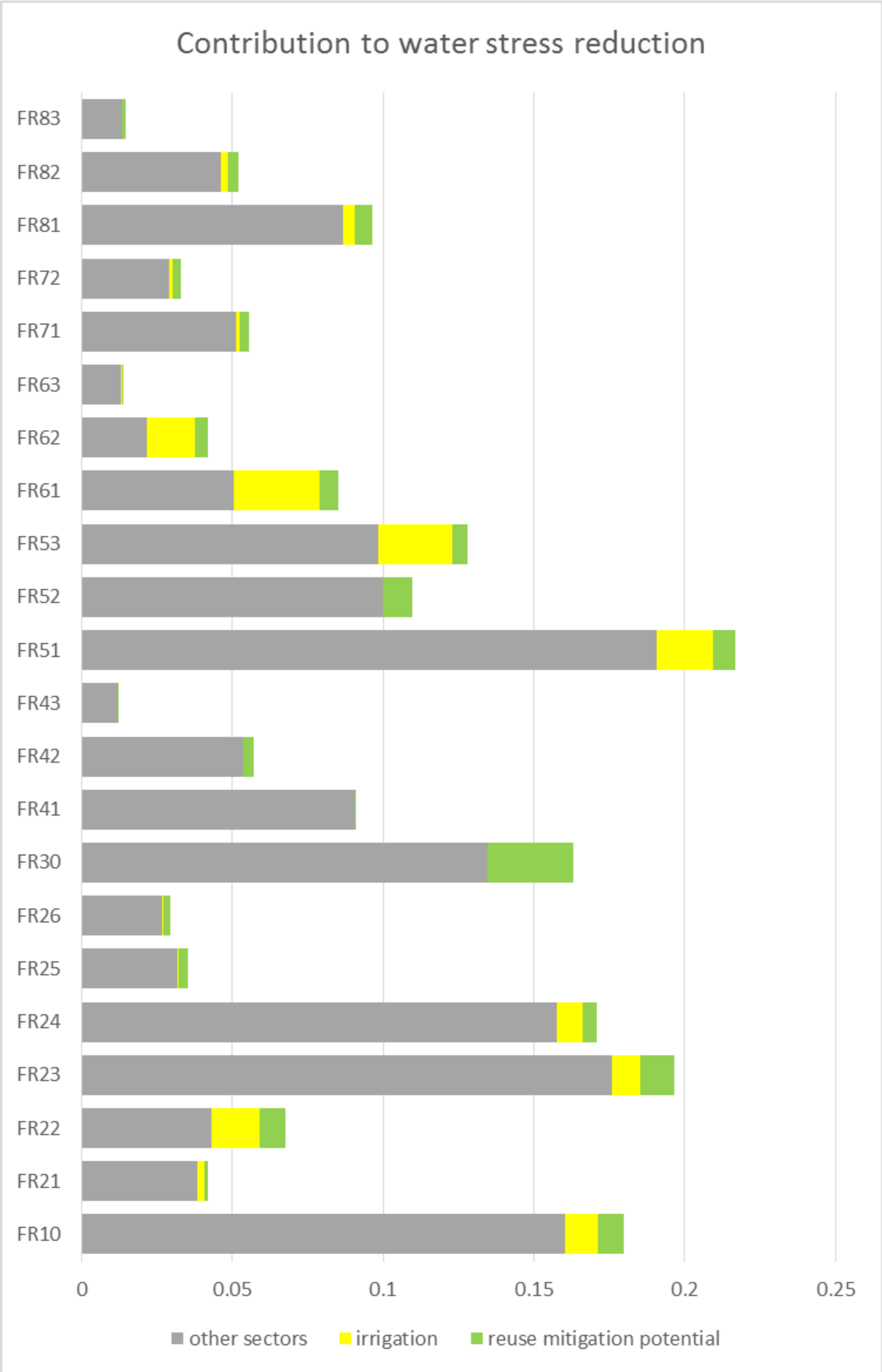
Source: JRC

Figure 46 –human appropriation of water surplus, with and without water reuse, under baseline conditions: ES, PT.



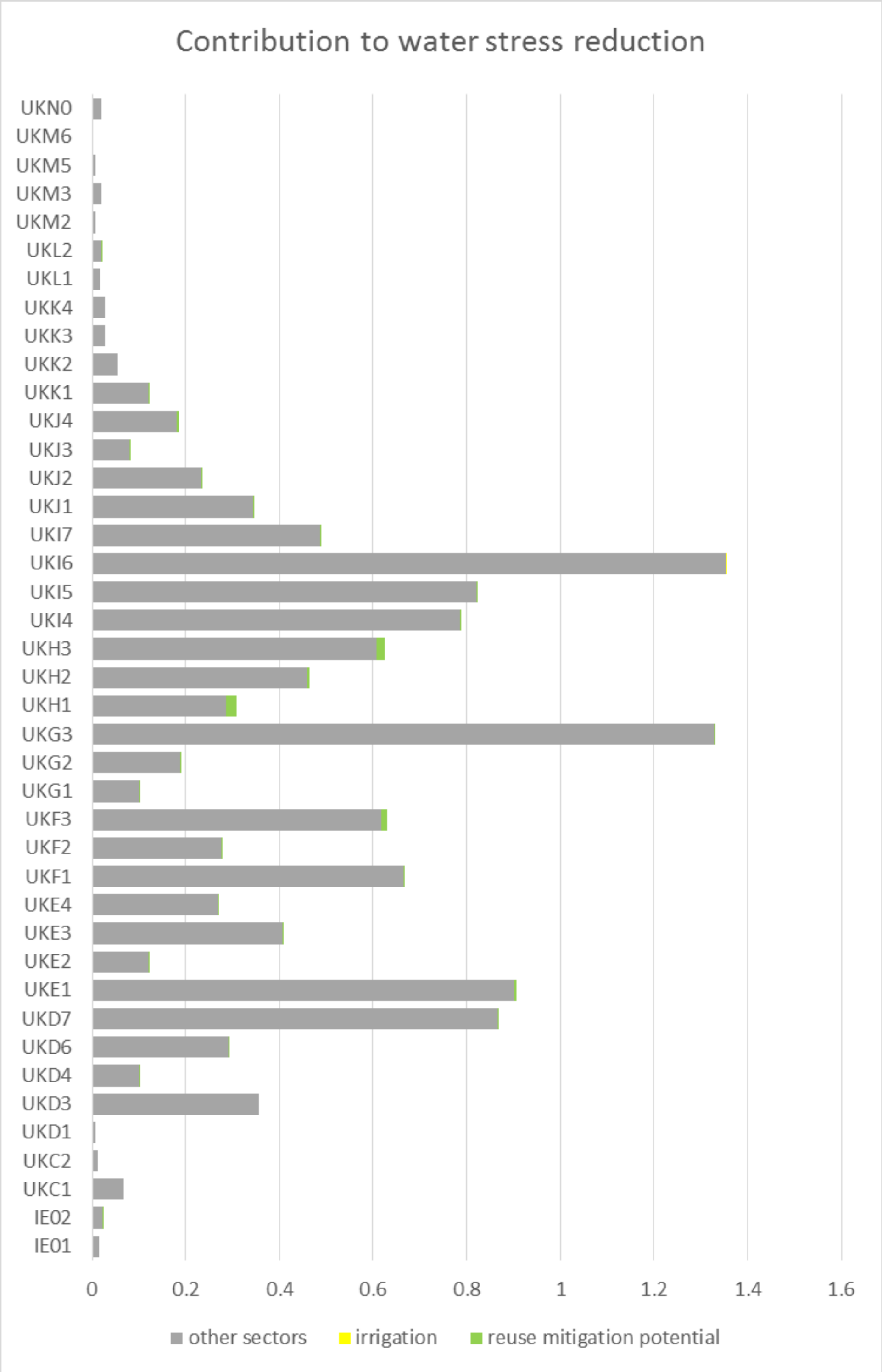
Source: JRC

Figure 47 –human appropriation of water surplus, with and without water reuse, under baseline conditions: FR.



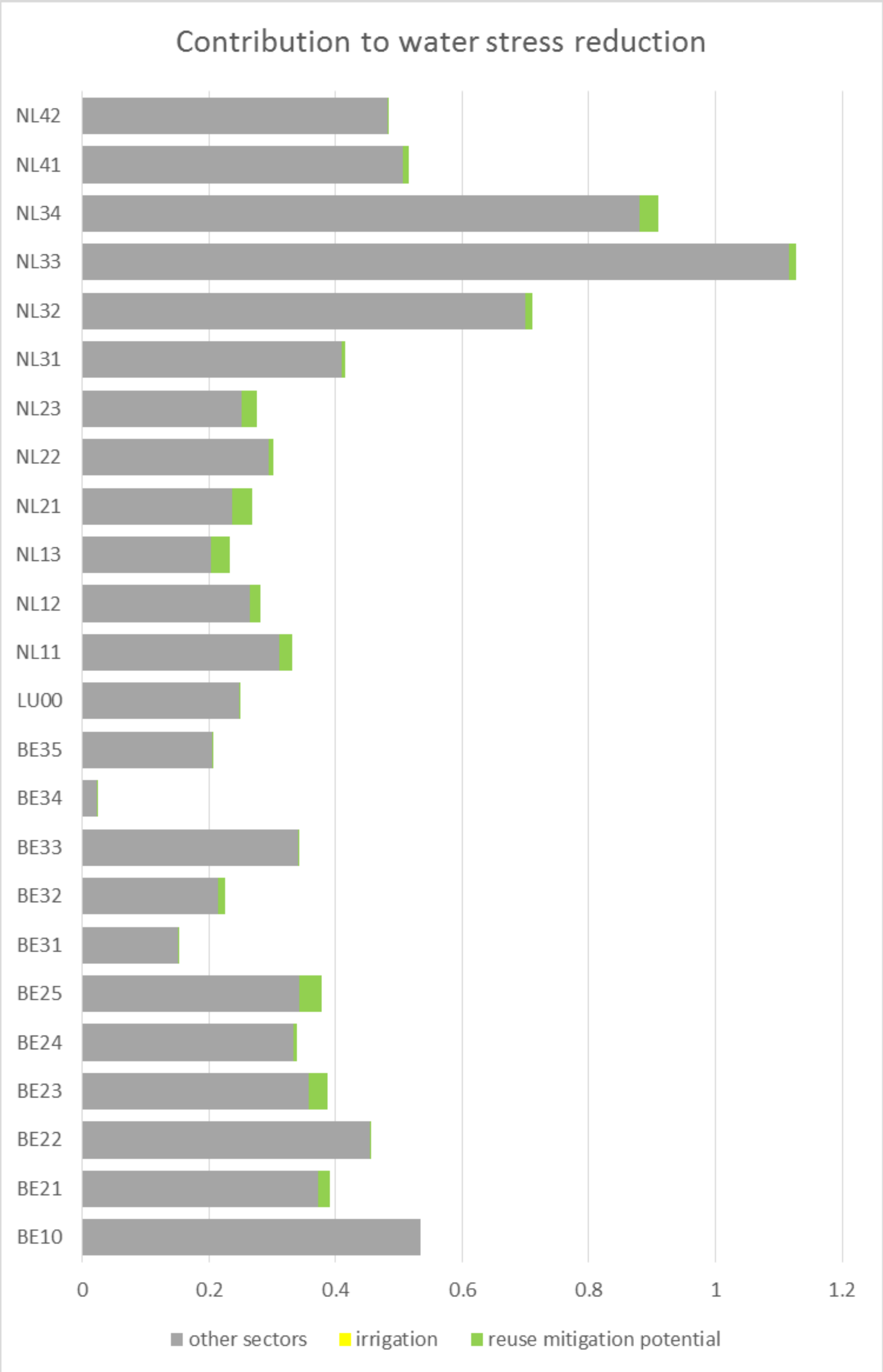
Source: JRC

Figure 48 –human appropriation of water surplus, with and without water reuse, under baseline conditions: IE, UK.



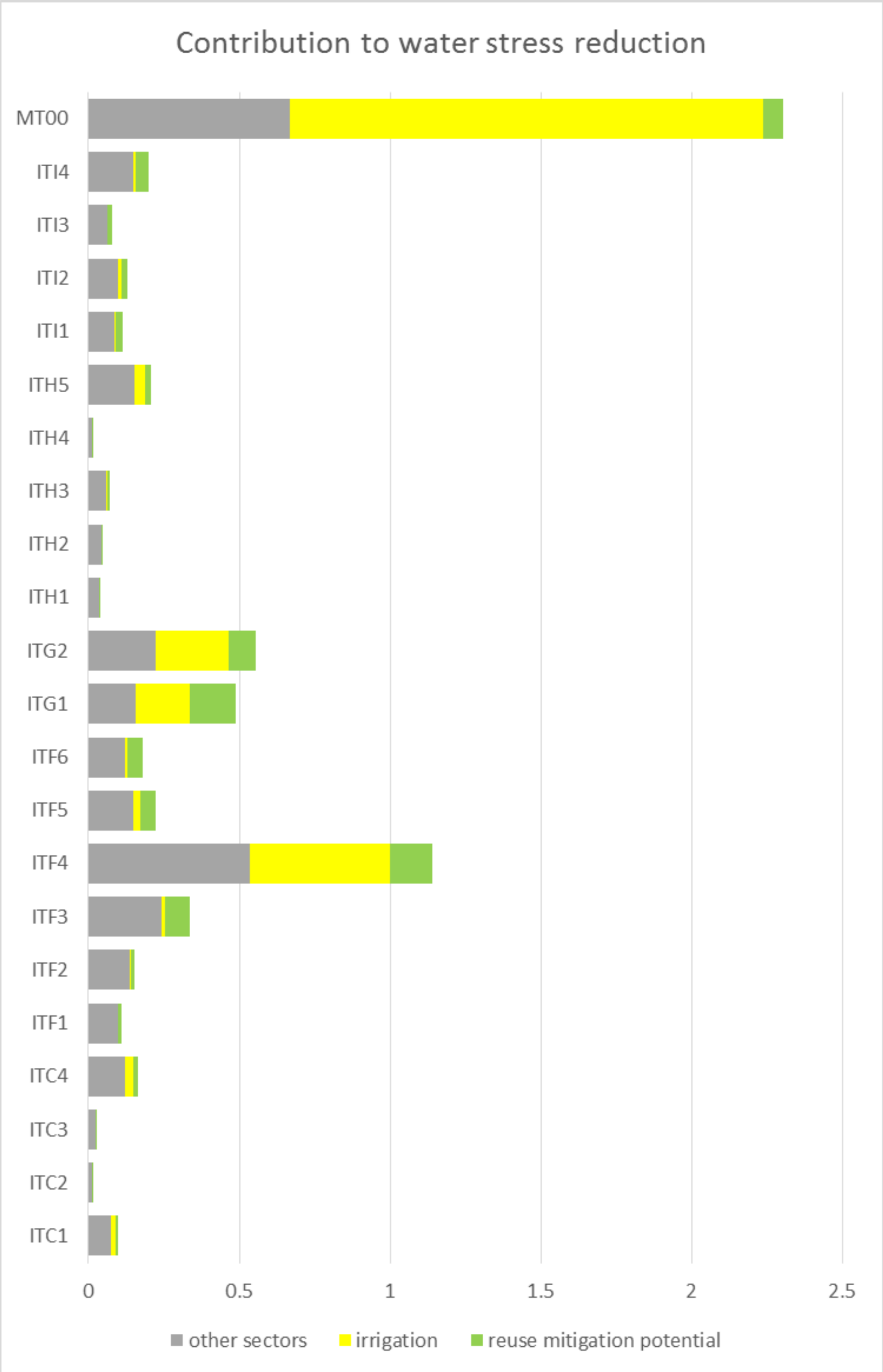
Source: JRC

Figure 49 –human appropriation of water surplus, with and without water reuse, under baseline conditions: NL, BE, LU.



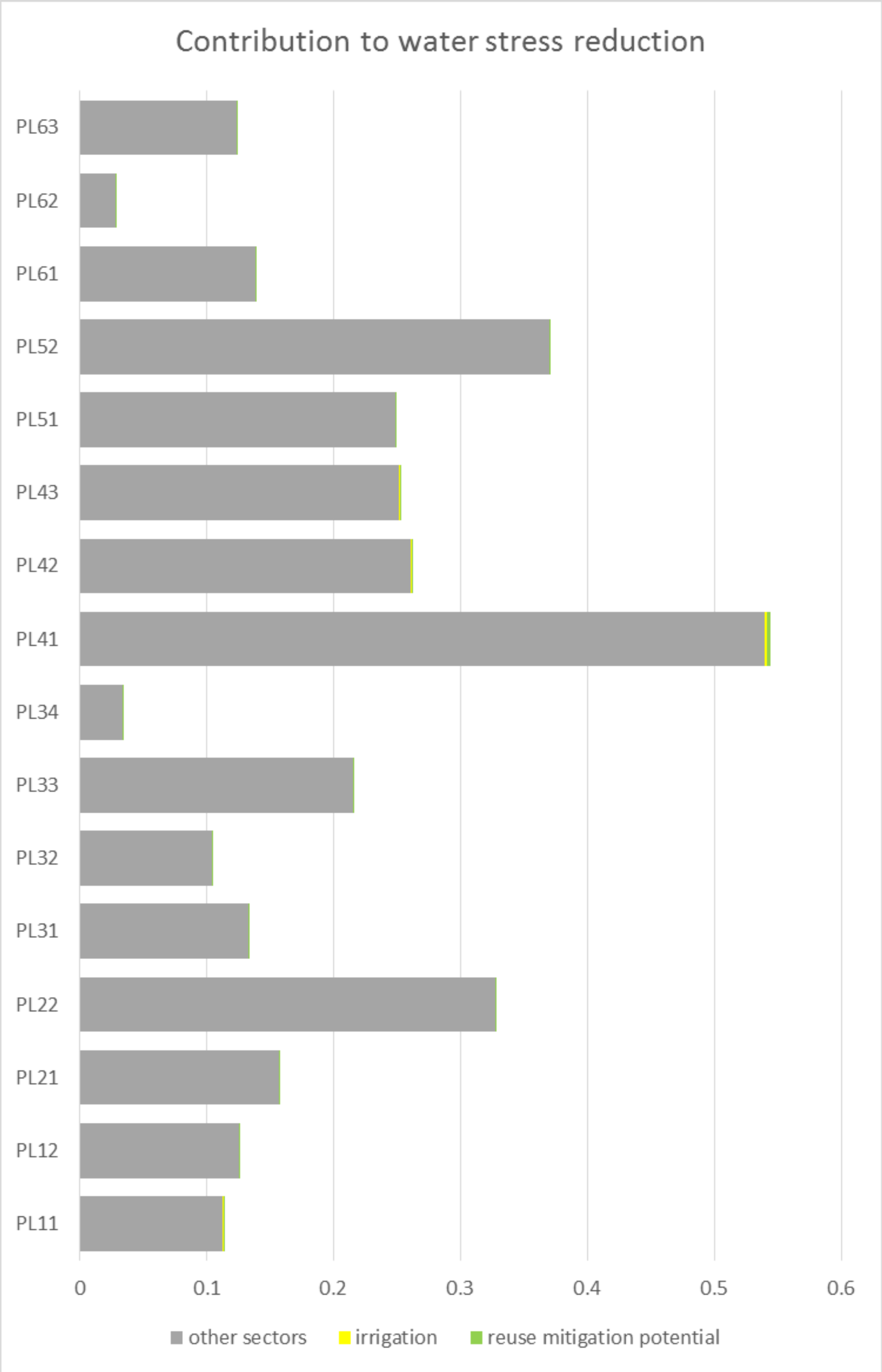
Source: JRC

Figure 50 –human appropriation of water surplus, with and without water reuse, under baseline conditions: IT, MT.



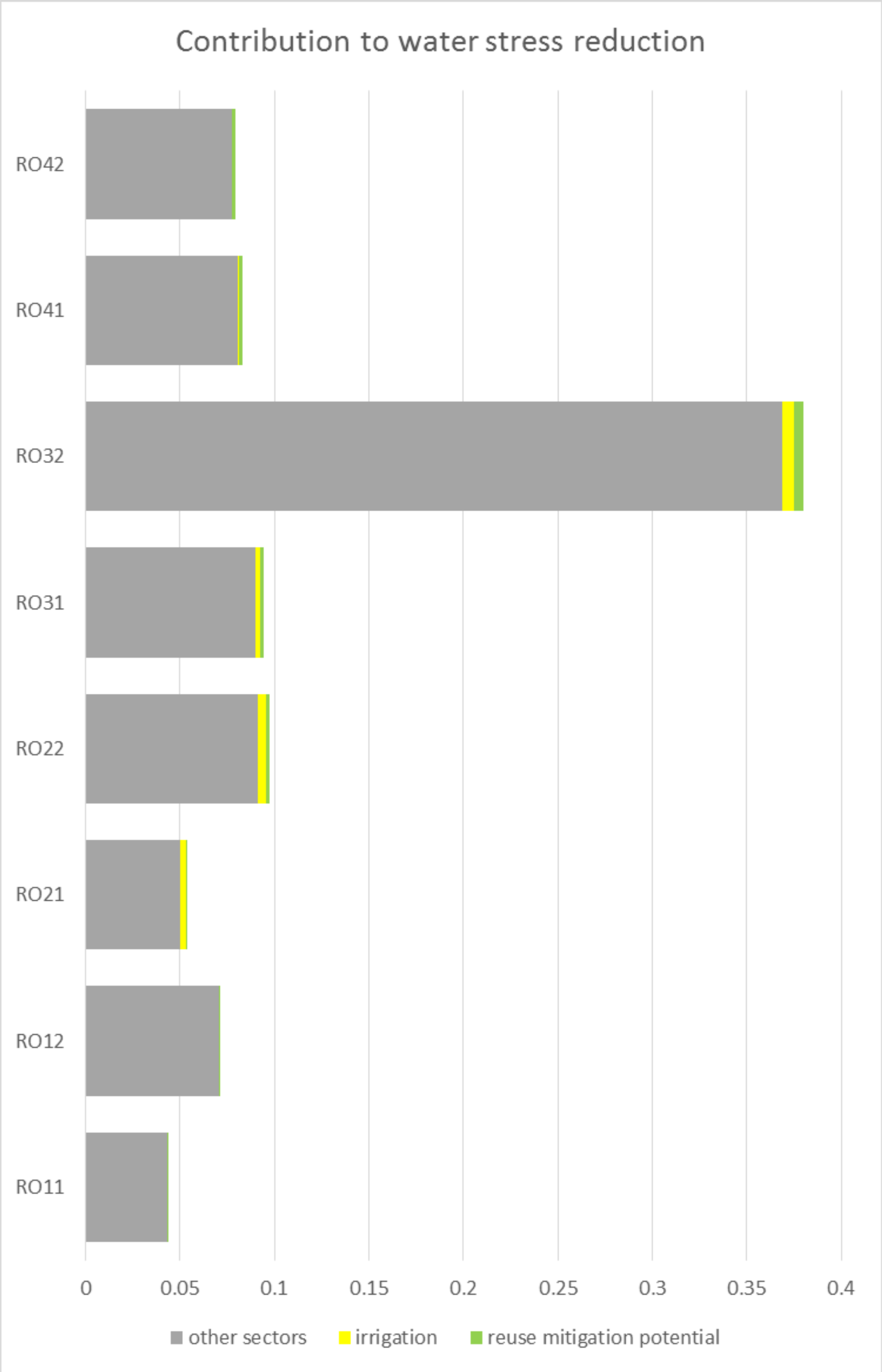
Source: JRC

Figure 51 –human appropriation of water surplus, with and without water reuse, under baseline conditions: PL.



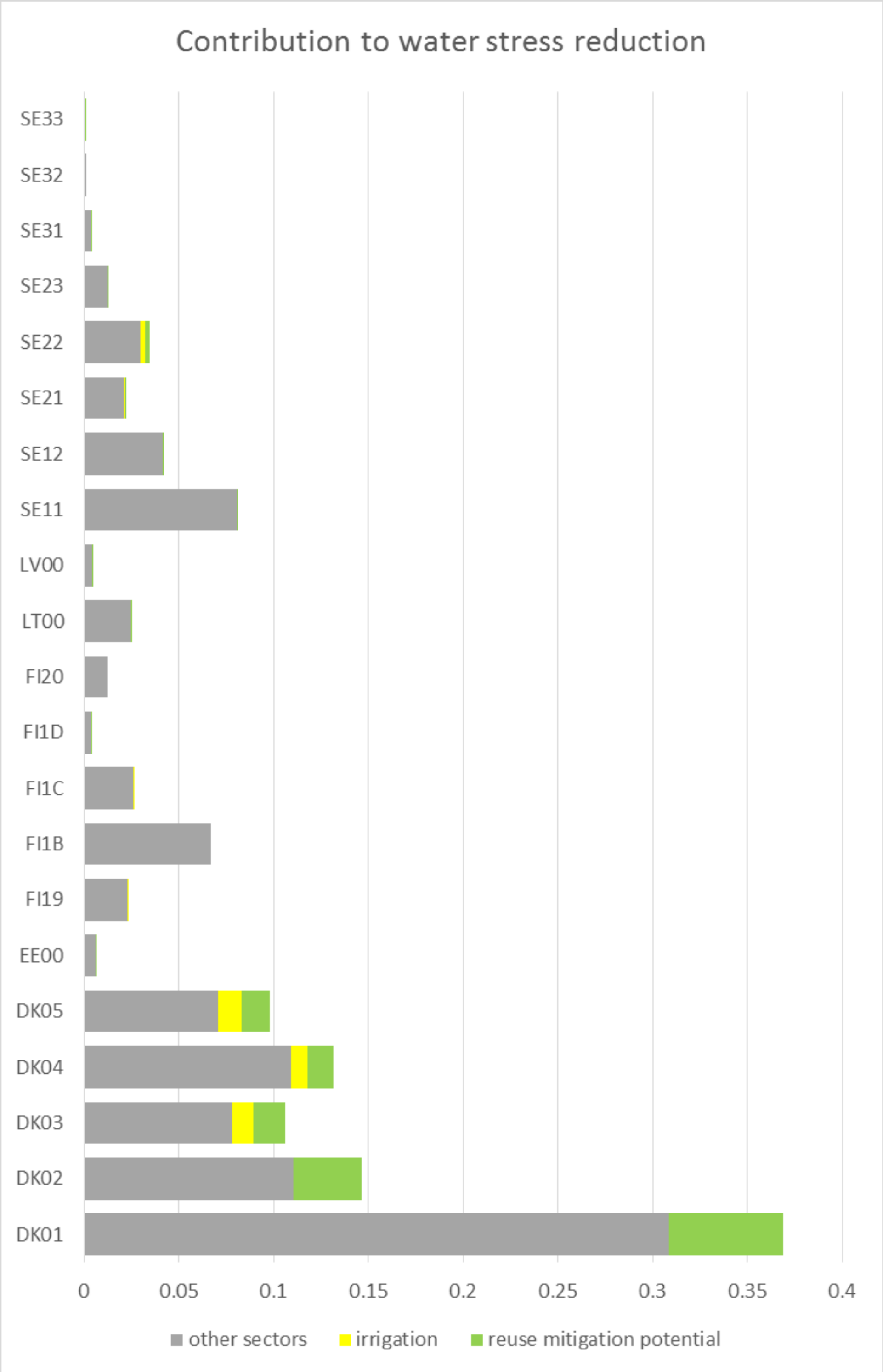
Source: JRC

Figure 52 –human appropriation of water surplus, with and without water reuse, under baseline conditions: RO.



Source: JRC

Figure 53 –human appropriation of water surplus, with and without water reuse, under baseline conditions: DK, SE, FI, LV, LT, EE.

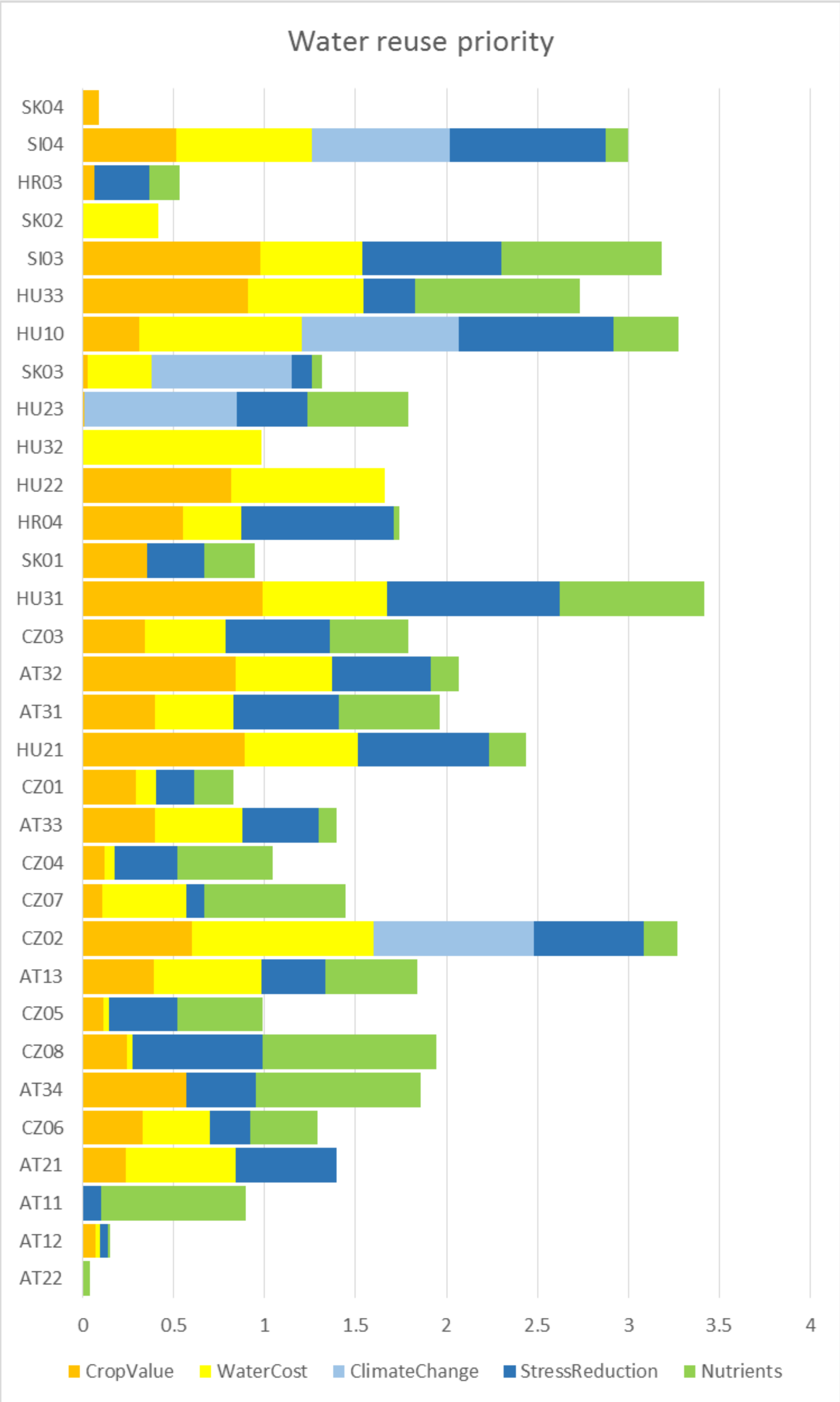


Source: JRC

Annex 3– Criteria for the prioritization of water reuse for irrigation, by level-2 NUTS regions

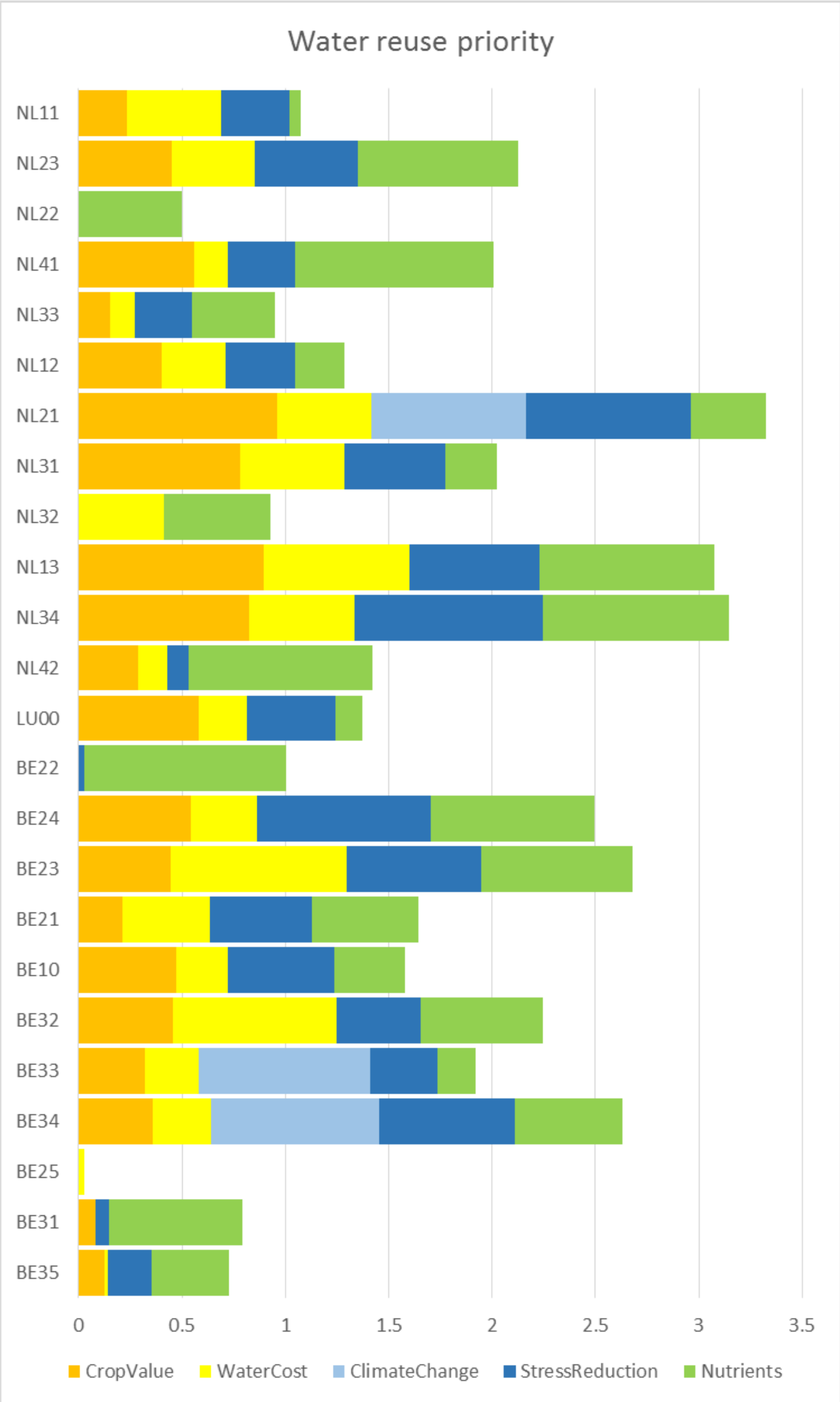
The graphs below visualize, for each level-2 NUTS region in the EU, the contributions to the water appropriation indicator of Equation 9 from irrigation, from other sectors, and the share of the irrigation contribution that could be mitigated through reuse (assuming no constraints on water reuse costs).

Figure 54. Priority for reuse at NUTS2 level: AT, CZ, HU, HR, SI, SK



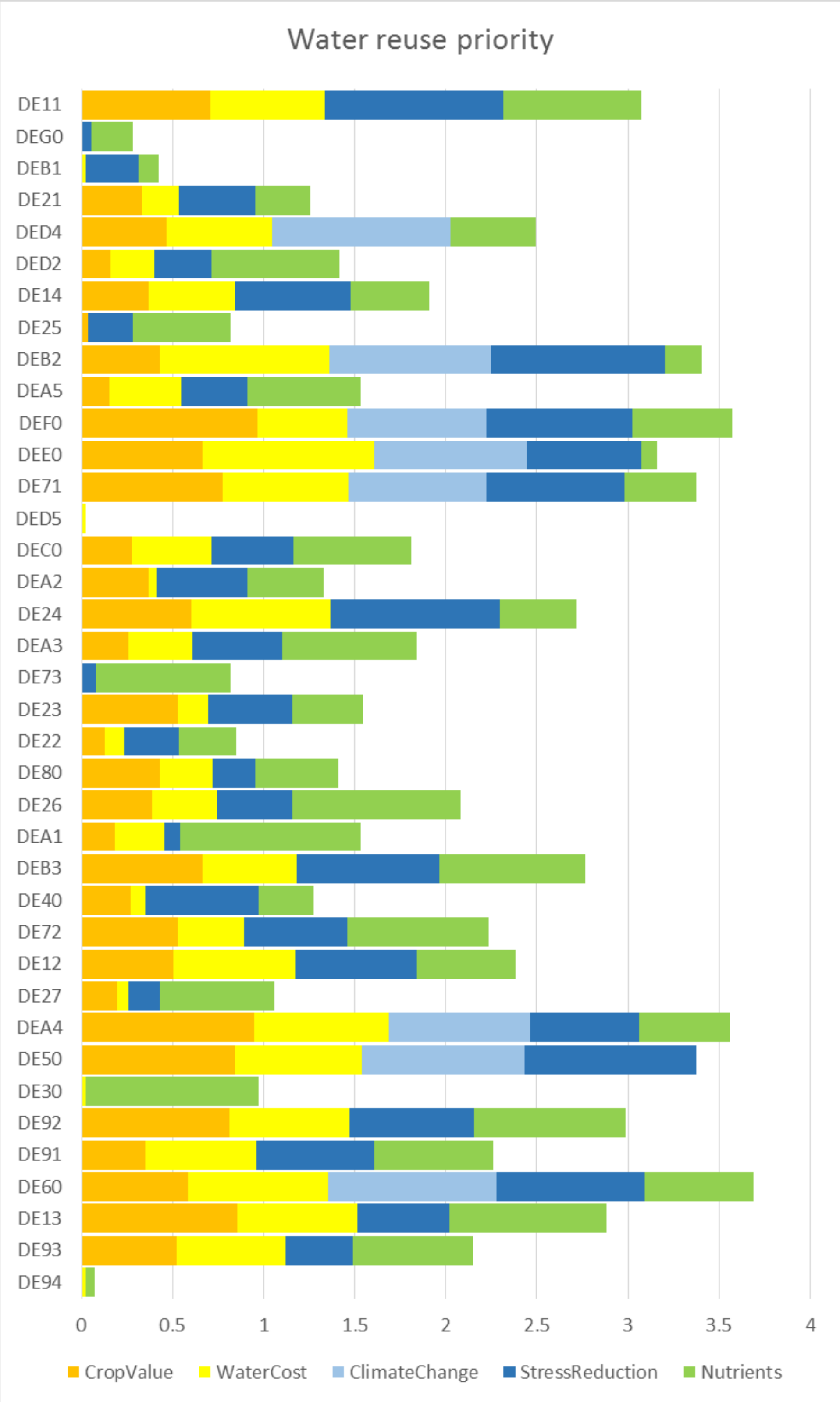
Source: JRC

Figure 55. Priority for reuse at NUTS2 level: BE, NL, LU



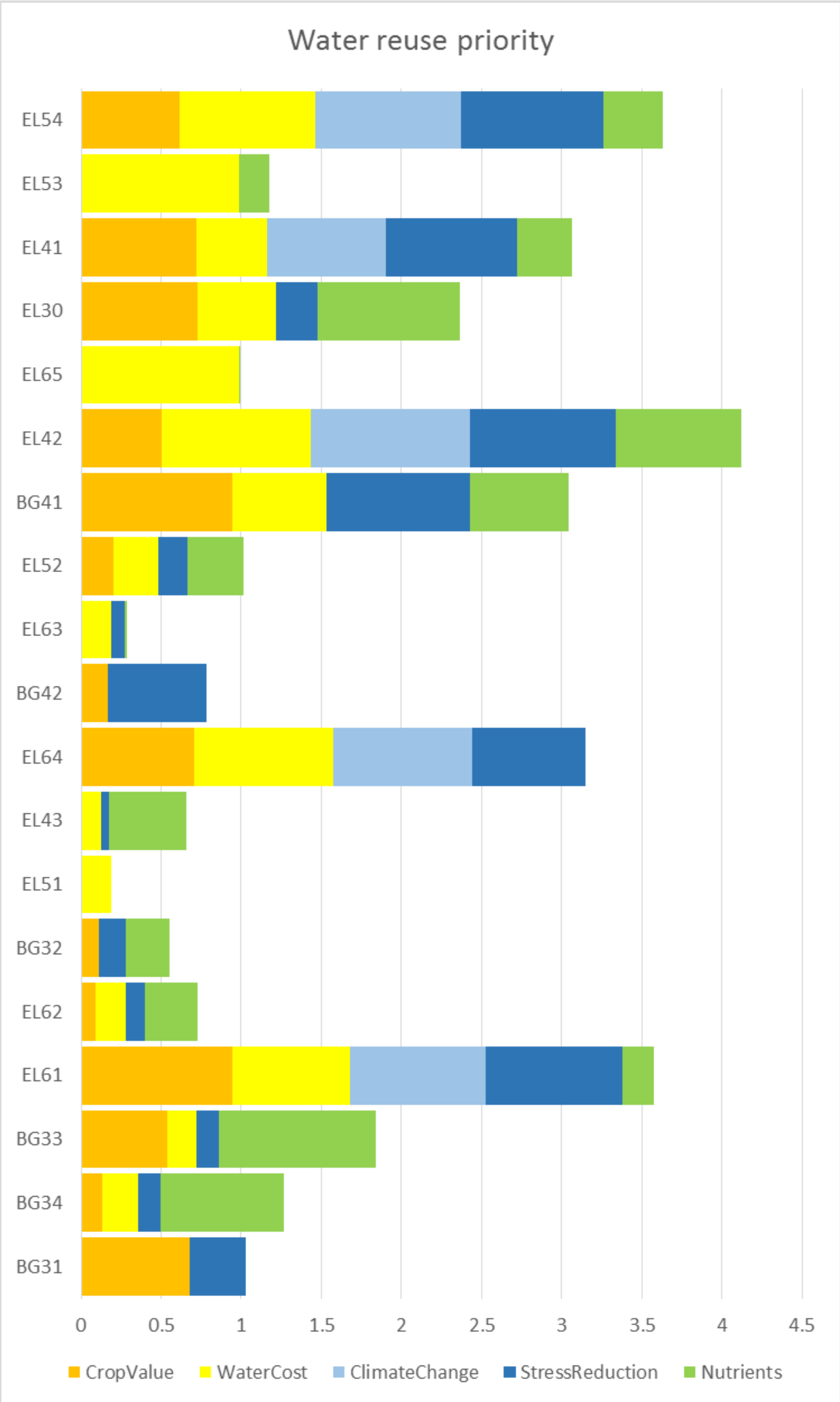
Source: JRC

Figure 56. Priority for reuse at NUTS2 level: DE



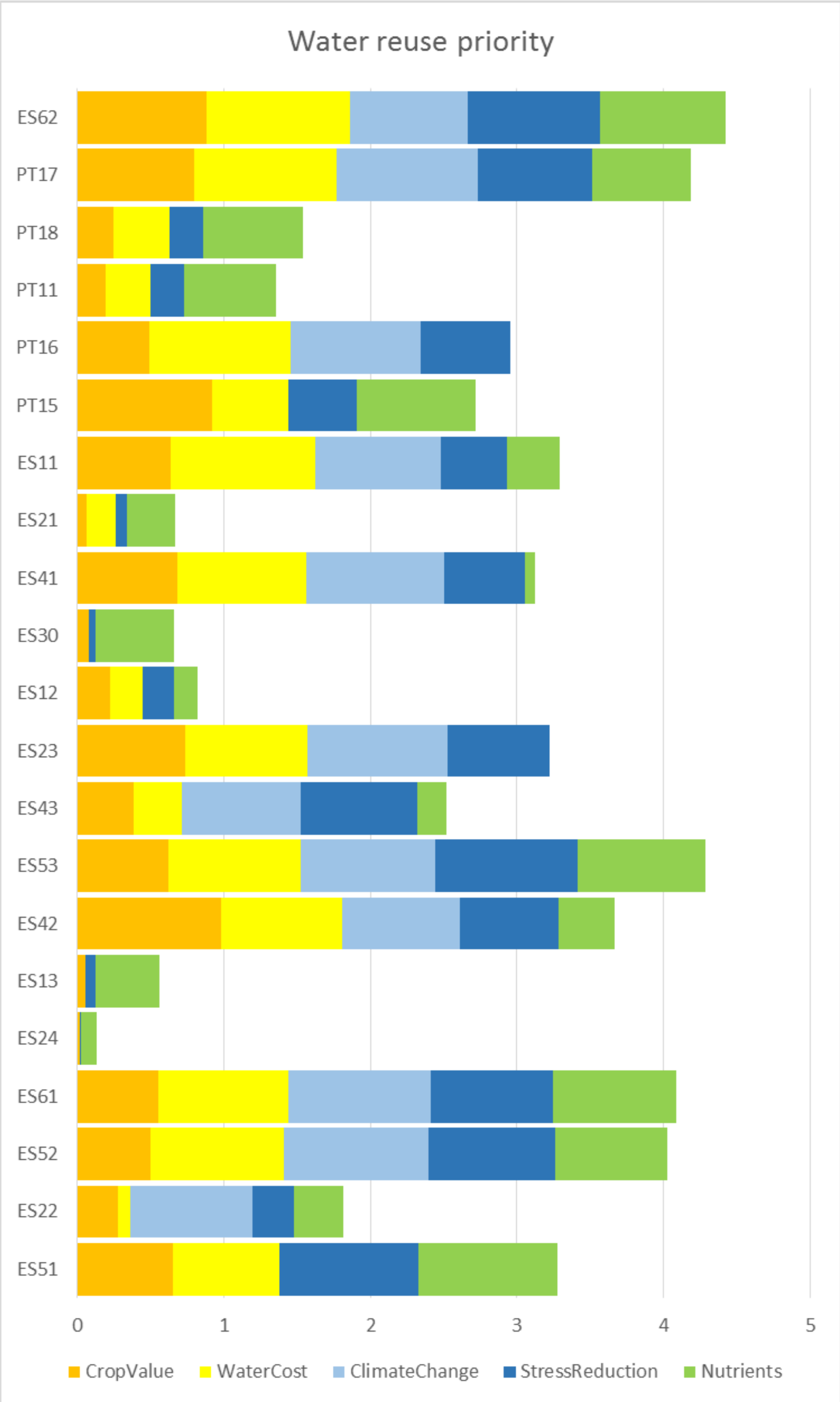
Source: JRC

Figure 57 . Priority for reuse at NUTS2 level: EL, BG



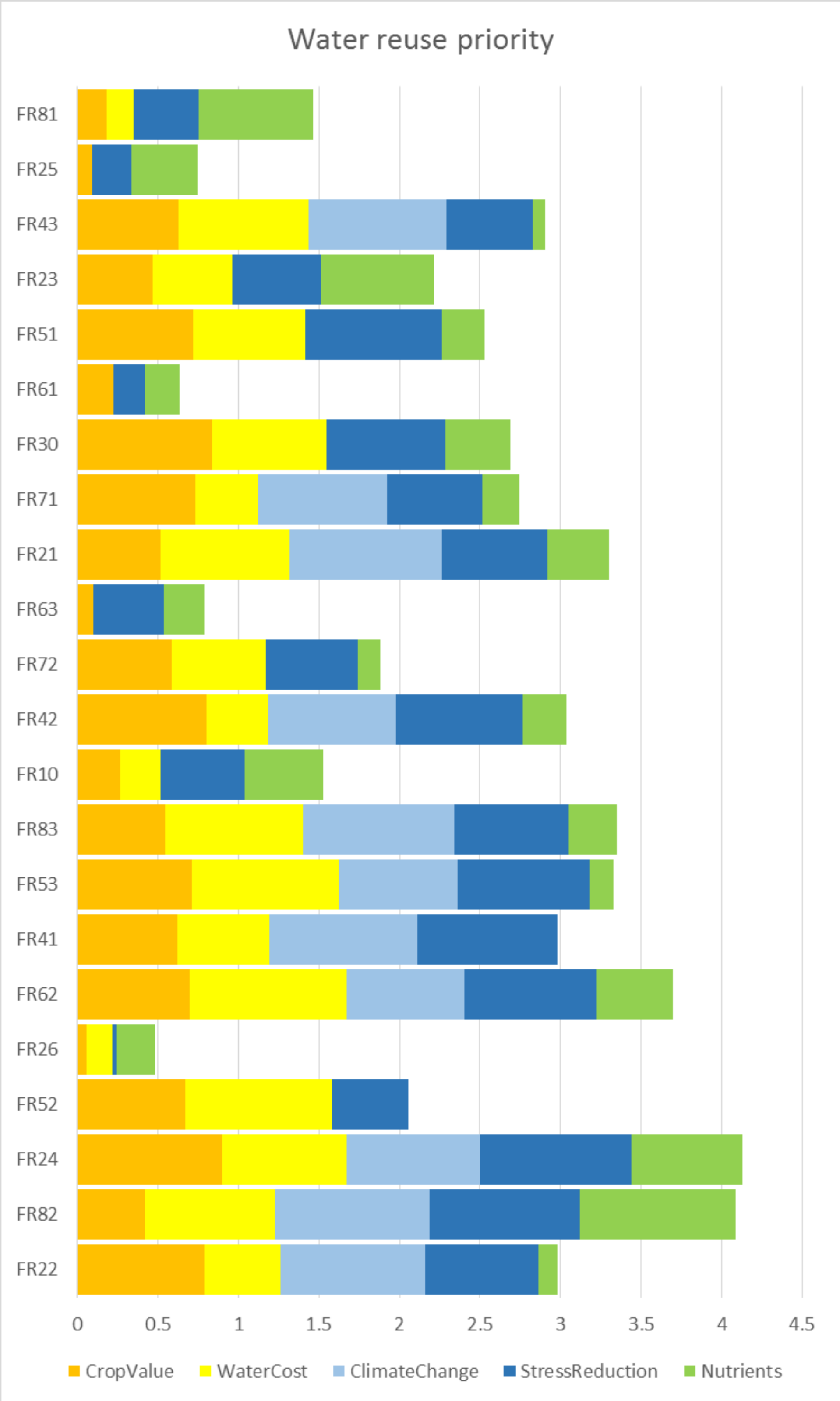
Source: JRC

Figure 58. Priority for reuse at NUTS2 level: ES, PT



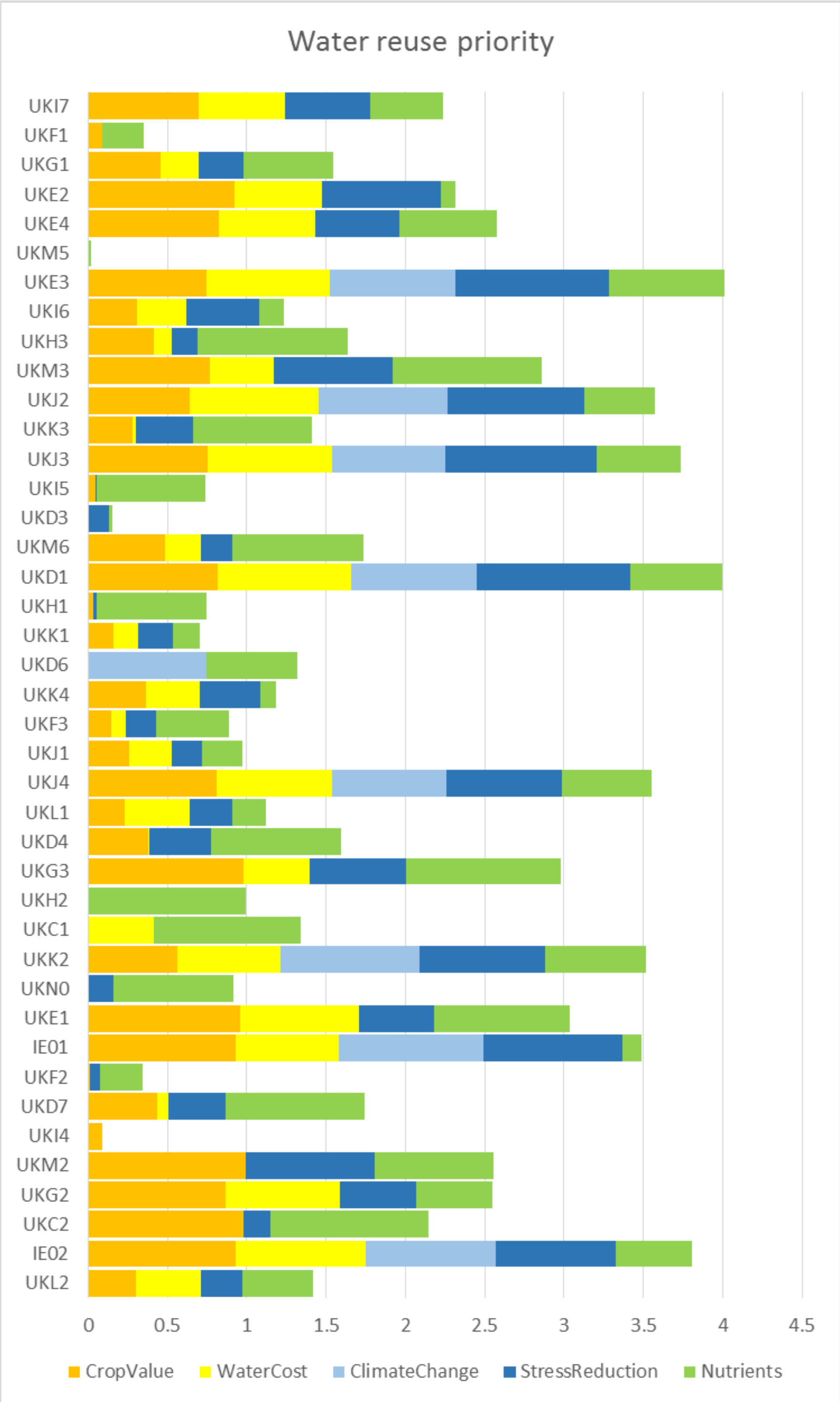
Source: JRC

Figure 59. Priority for reuse at NUTS2 level: FR



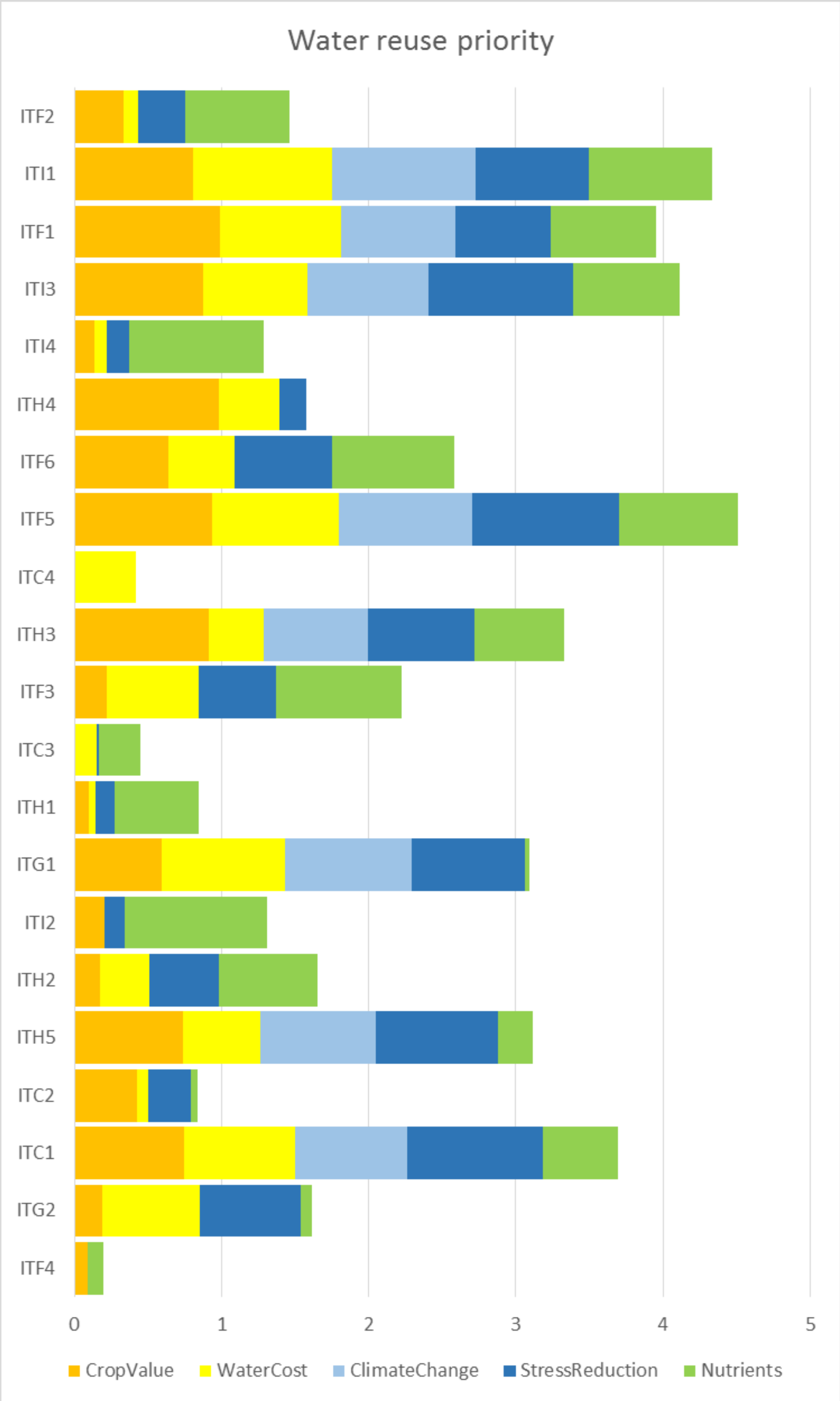
Source: JRC

Figure 60. Priority for reuse at NUTS2 level: UK, IE



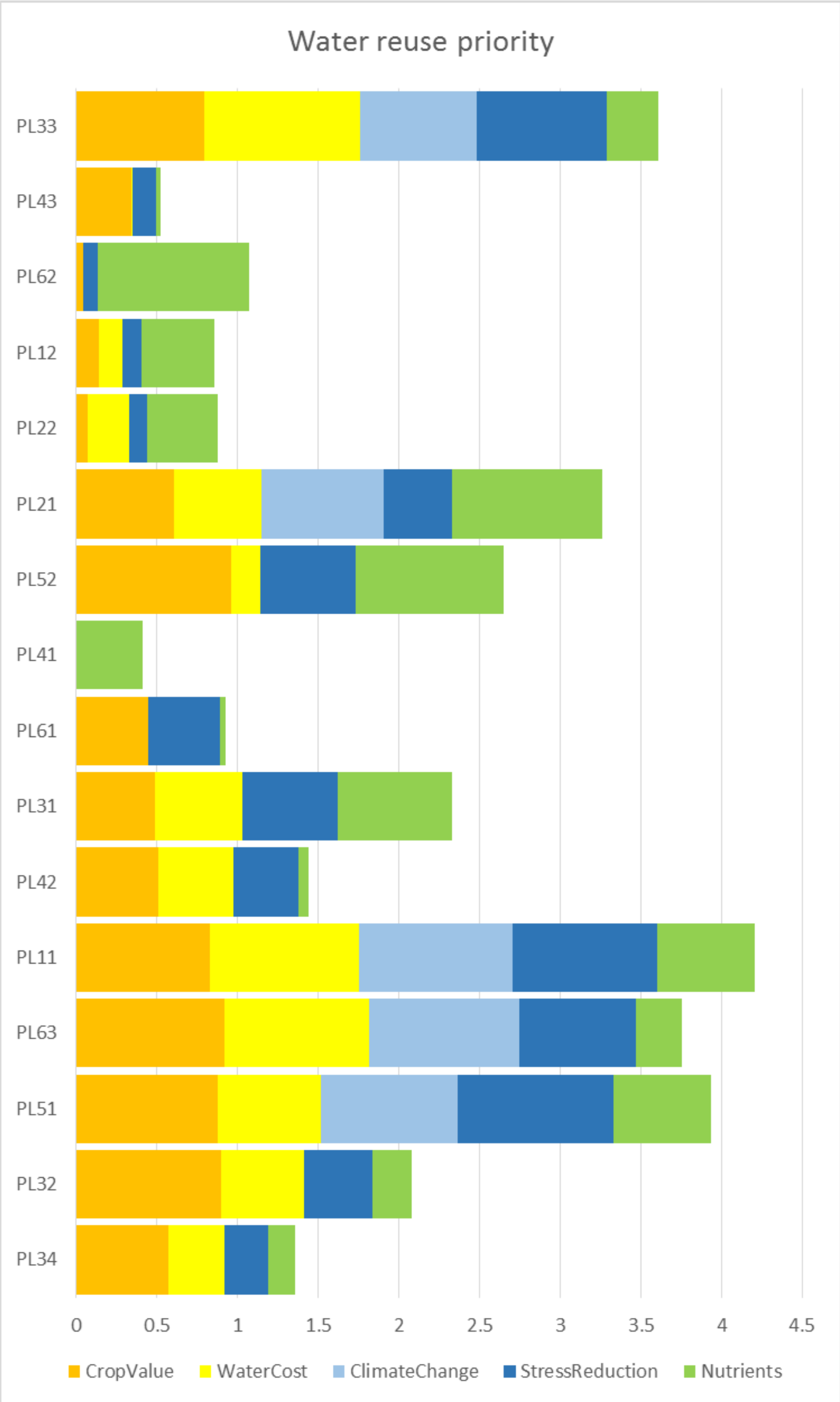
Source: JRC

Figure 61. Priority for reuse at NUTS2 level: IT



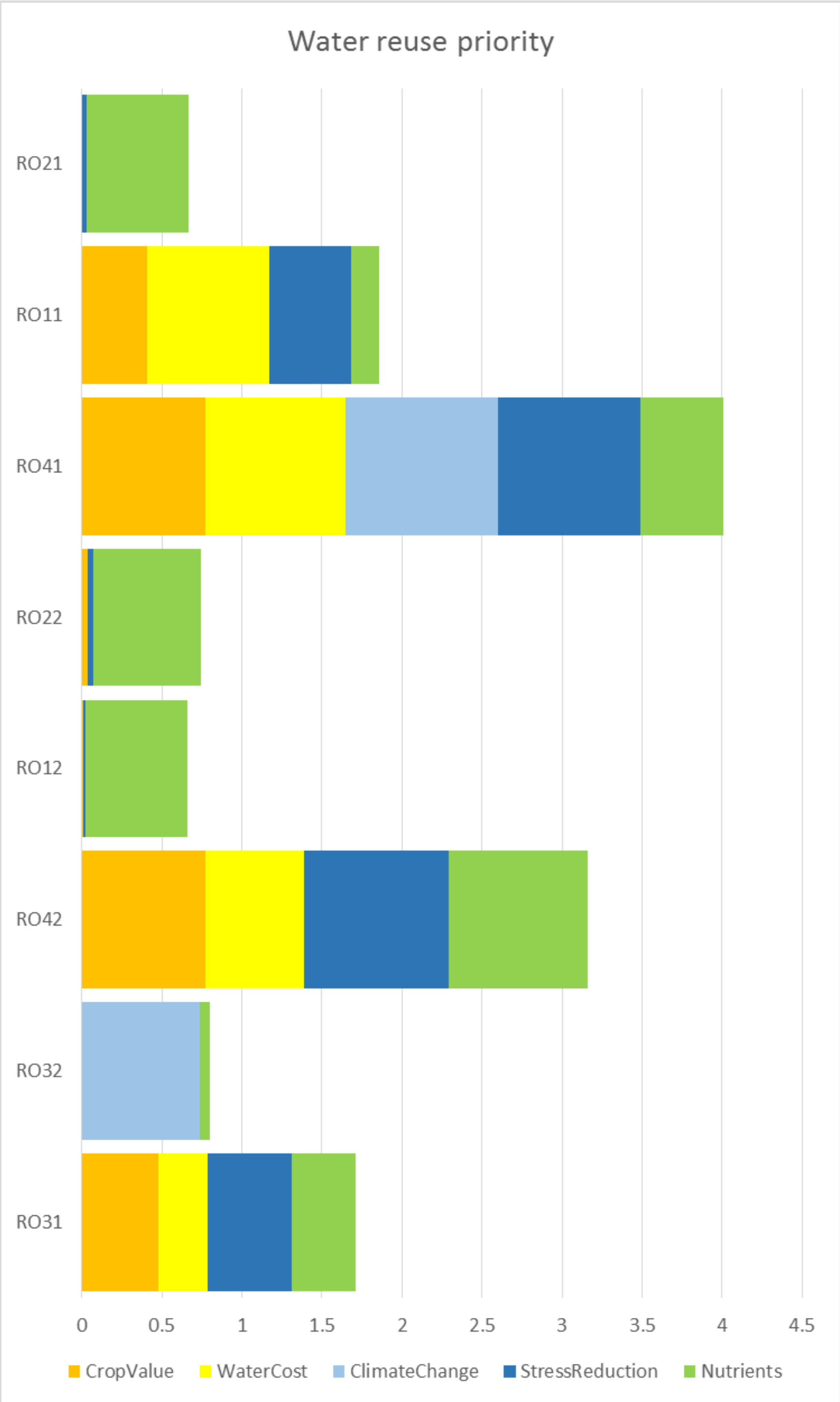
Source: JRC

Figure 62. Priority for reuse at NUTS2 level: PL



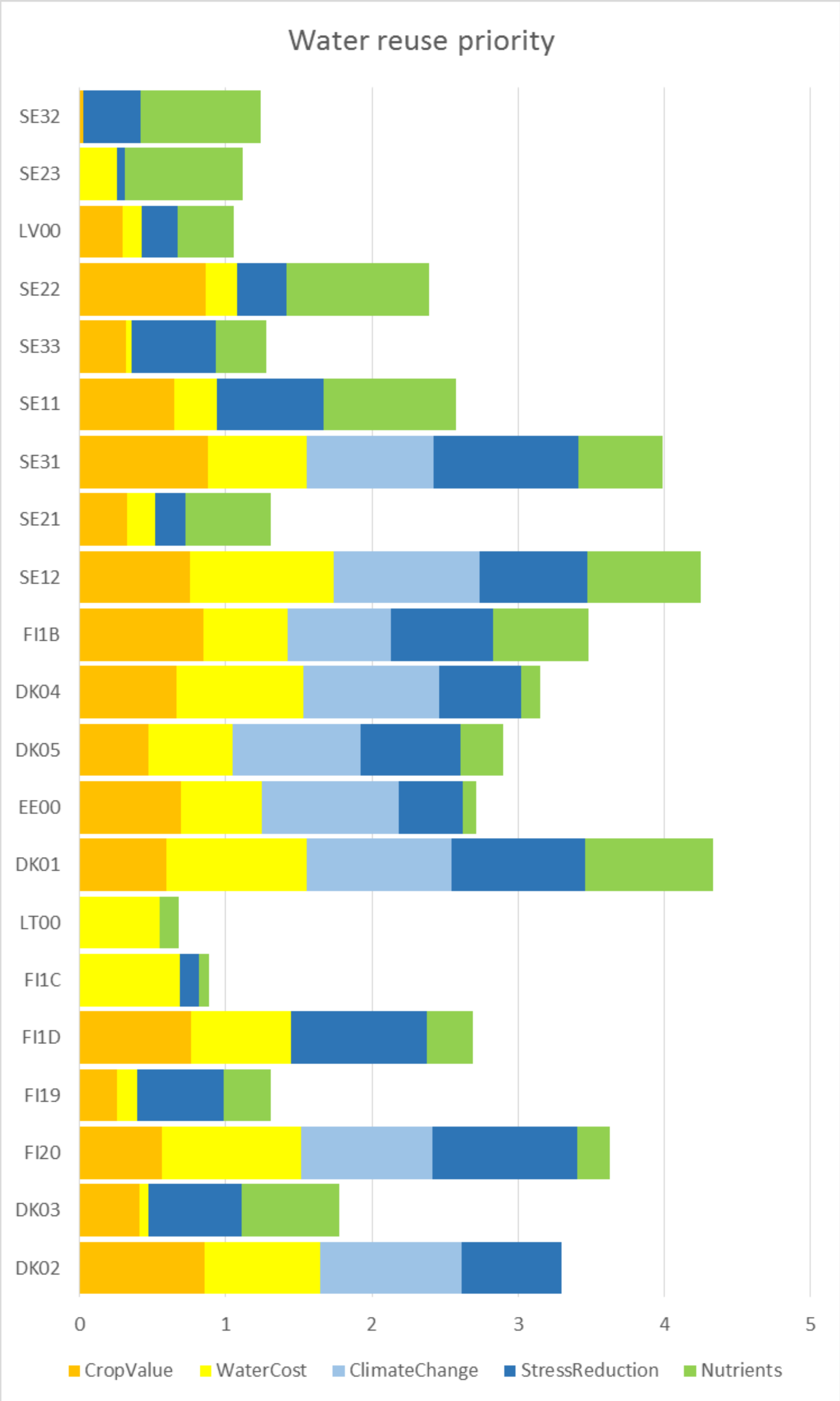
Source: JRC

Figure 63. Priority for reuse at NUTS2 level: RO



Source: JRC

Figure 64. Priority for reuse at NUTS2 level: DK, SE, FI, EE, LT, LV



Source: JRC

Annex 4– Water needs of the new energy system in 2022

Introduction

The EU energy sector's water needs are a critical aspect of its operations, with significant implications for water resources management and policy-making. The JRC has estimated the water needs of the EU energy sector related to the extraction of primary energy products (coal, natural gas, primary solid biomass, etc.) and the transformation into final energy products (crude oil refining, biofuel production, hydropower generation, or the cooling of thermal power plants).

The estimation builds upon the assumptions described in previous JRC reports [1, 2], but this update is also based on the latest energy balances from EUROSTAT [3] (with data from 2022) and the ongoing work to develop the EU Energy Atlas of the Energy and Industry Geography Lab [4]. The results consist of four maps available from the JRC Data Catalogue [5] at 1x1 km resolution and consider both freshwater and non-fresh water resources.

Water withdrawal

In 2022, the EU energy sector withdrew 56.2 billion m^3 of freshwater, and 75.2 billion m^3 of non-fresh water (mostly seawater).

The power sector was by far the most water-intensive part of the energy system, withdrawing almost 97 % of all water resources (54.5 billion m^3 of freshwater and 72.4 billion m^3 of non-freshwater) mostly for the cooling of thermal power plants.

The refining of petroleum products required 2.1 % of the resources (0.1 billion m^3 of freshwater and 2.7 billion m^3 of non-freshwater, since there are only a few refineries located inland).

The operation of coke oven plants and blast furnaces needed 0.52 % of the water withdrawals (0.7 billion m^3 of freshwater).

Coal mining was the fourth most water-intensive activity, accounting for 0.44 % of the water withdrawals (0.6 billion m^3 of freshwater).

The production of primary solid biomass, such as energy crops and fuelwood, required the withdrawal of 0.2 % of the resources (0.3 billion m^3 of freshwater).

Other activities such as the extraction of crude oil, natural gas, peat and oil shales, or the production of charcoal, biofuels, or energy products from waste also needed water resources, but in much smaller quantities (less than 0.1% for all of them together).

Water consumption

Part of the withdrawn water resources were consumed, mainly due to evaporation in cooling devices and water reservoirs. Water consumption amounted respectively to 6.7 billion m^3 of freshwater and 0.8 billion m^3 of non-fresh water in 2022.

The power sector consumed more than 95 % of all water resources (6.5 billion m^3 of freshwater and 0.7 billion m^3 of non-freshwater). About two thirds of this consumption was due to the evaporation of water in reservoirs. Most reservoirs are used for multiple purposes apart from hydropower generation (such as irrigation, water supply, navigation and recreation) and there are neither enough data nor a straightforward methodology to allocate evaporative losses to the different activities. Thus, this figure rather represents an upper bound of the actual amount of water consumed for hydropower, considering that in the EU 30 % of reservoirs associated to large dams are single-use hydropower.

The refining of petroleum products accounted for 3.4 % of the consumption (0.1 billion m^3 of freshwater and 0.1 billion m^3 of non-freshwater).

The operation of coke oven plants and blast furnaces consumed 0.9 % of the water resources (0.07 billion m^3 of freshwater). Coal mining consumed 0.28 % of the resources (0.02 billion m^3 of freshwater). The water consumed by all other activities was negligible.

Comparison with previous estimations and available data

Table 6 shows that the current estimation is in line with previous JRC works [1]. It is also consistent with the observed long-term trend of decreasing water requirements for energy production originated by the spread of wind and solar energy and the closure of thermal power plants.

EUROSTAT provides some statistics on water use [6, 7, 8] but the reporting is very irregular and data for key countries such as Germany, France, or Italy are missing, and EUROSTAT only considers freshwater resources. Despite EUROSTAT data are not fully comparable with the JRC estimations for those reasons, **Table 6** shows that the JRC results are plausible and within a similar order of magnitude.

Table 6 – Comparison of freshwater withdrawals for energy purposes in the EU in different years (billion m^3)

EUROSTAT use categories	JRC 2022 [current estimation]	JRC 2015 [1]	EUROSTAT 2020	EUROSTAT 2022
Agriculture, forestry and fishing	0.3	1.3	24.8	1.1
Mining and quarrying	0.6	0.9	0.5	0.4
Production and distribution of electricity	54.5	60.7	31.9	8.1
Basic metals	0.1	0.0	0.9	0.3
Coke, refined petroleum products, and chemical products	0.7	0.1	6.3	2.0
Total	56.2	63.0	64.5	12.0

Source: JRC and EUROSTAT, 2025

Notes:

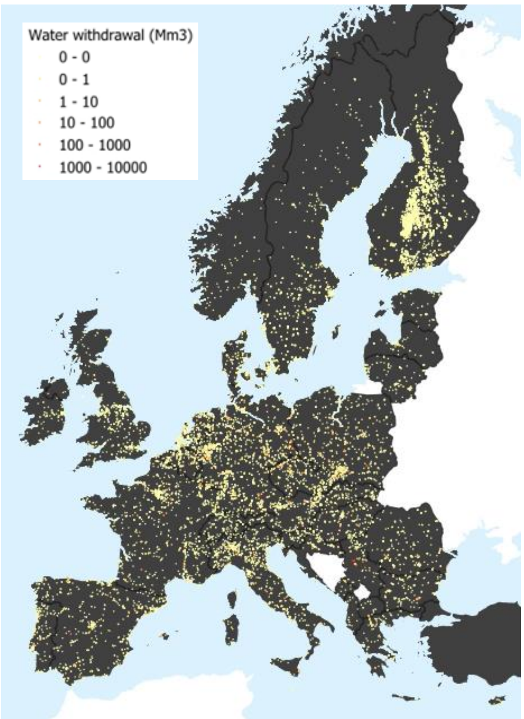
- "Agriculture, forestry and fishing" includes all agricultural activities, not only energy-related.
- "Mining and quarrying" includes all mining activity, not only energy-related
- JRC figures include all water needs for "Production and distribution of electricity" while EUROSTAT only reports cooling requirements.
- "Basic metals" covers the production of iron and steel as well as non-ferrous metals, but the JRC figures only reflect the operation of coke oven plants and blast furnaces, the only parts of the basic metals sector that are considered energy-producing facilities in the energy balances.
- "Coke, refined petroleum products, and chemical products" includes the needs of the chemical industry, while the JRC figures only take into account the energy-producing facilities (coke ovens and oil refineries).

Spatial patterns of water use for energy purposes

At national scale, five countries withdrew almost two thirds of the freshwater resources (36.4 billion m^3): France (19 %), Germany (16 %), Poland (10 %), Belgium (10 %), and Bulgaria (9%). Almost 70% of the freshwater consumption, 4.6 billion m^3, took place in MS: Germany (18 %), France (17 %), Sweden (17 %), Austria (7 %), and Spain (7 %). Only three MS withdrew 67 % of non-freshwater resources: France (29 %), Sweden (26 %), and Italy (12 %). Three quarters of the non-freshwater resources (0.6 billion m³) were consumed by five MS: France (18 %), Sweden (18 %), Spain (16 %), Italy (12 %), and the Netherlands (11 %). This distribution is mainly explained by the location of thermal power plants, refineries, and hydropower plants.

The current results cover the EU and the neighbouring countries (**Figure 65**, left), but they are provided at much at much finer 1x1 km resolution (**Figure 65**, right).

Figure 65 - Water withdrawals for energy purposes in 2022 across Europe (left) and detail for the Netherlands (right) (million m³)



Source: JRC, Energy and Industry Geography Lab, 2025

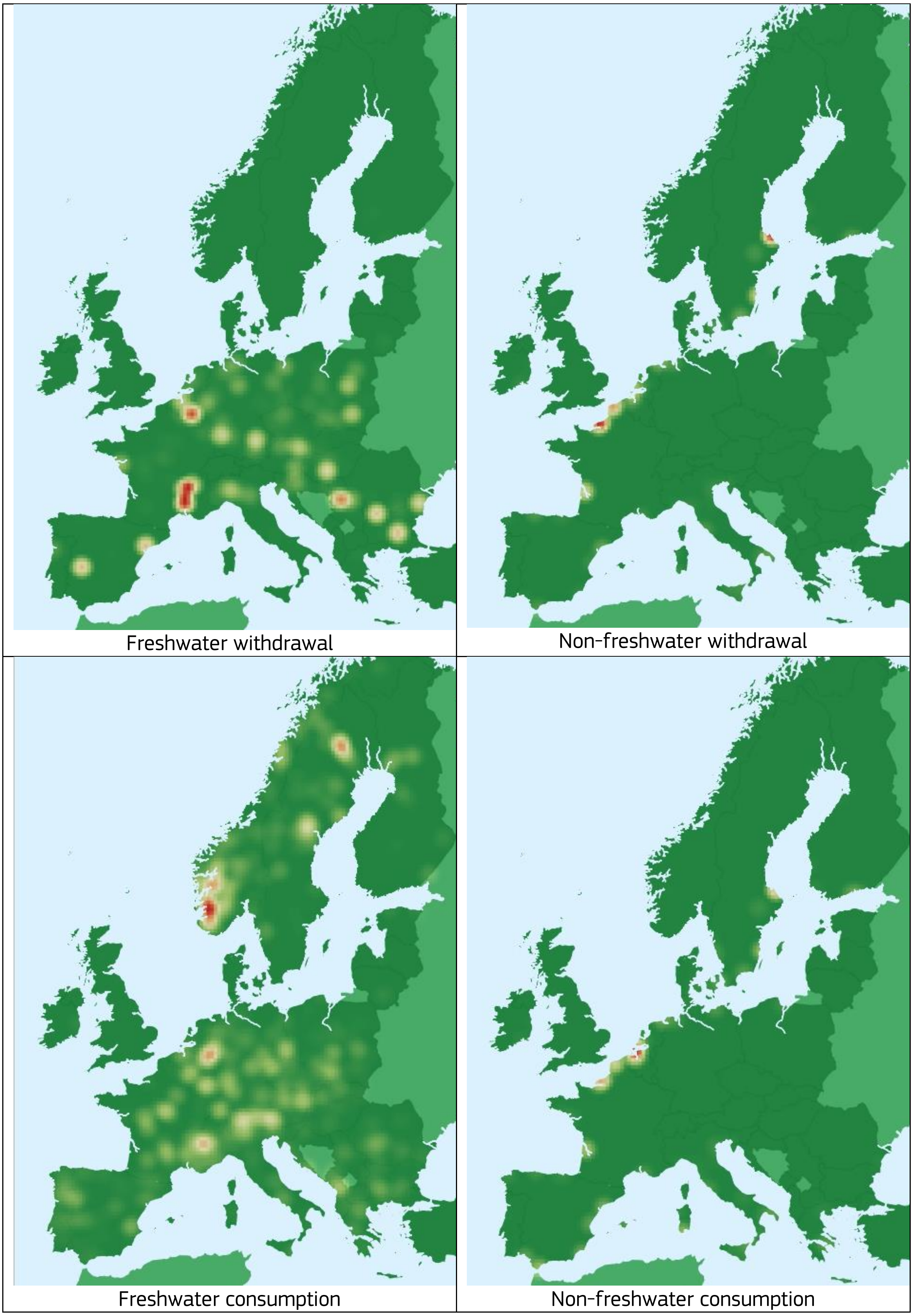
Heatmaps based on the detailed results clearly highlight the areas where most water resources were used.

The highest freshwater withdrawals took place near thermal power plants, often along major rivers such as the Rhine, the Rhone and the Danube (**Figure 66**, top left)

The pattern of freshwater consumption differs from the withdrawal. **Figure 66**, bottom left, shows higher consumption in mountain areas with significant hydropower capacity such as the Alps, or areas where power plants use cooling devices that produce significant evaporation.

As regards non-freshwater resources, withdrawals (**Figure 66**, top right) and consumption (**Figure 66**, bottom right) were concentrated near coastal refineries and thermal power plants, especially in the area Rotterdam-Antwerpen between the Netherlands and Belgium, the area Calais- Le Havre in France, and the Swedish nuclear plant in Forsmark in the Baltic Sea.

Figure 66- Heatmaps of the withdrawal and consumption of water resources across Europe



Source: JRC, Energy and Industry Geography Lab, 2025

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EUROSTAT, Annual freshwater abstraction by source and sector, https://ec.europa.eu/eurostat/databrowser/view/env_wat_abs/default/table?lang=en

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