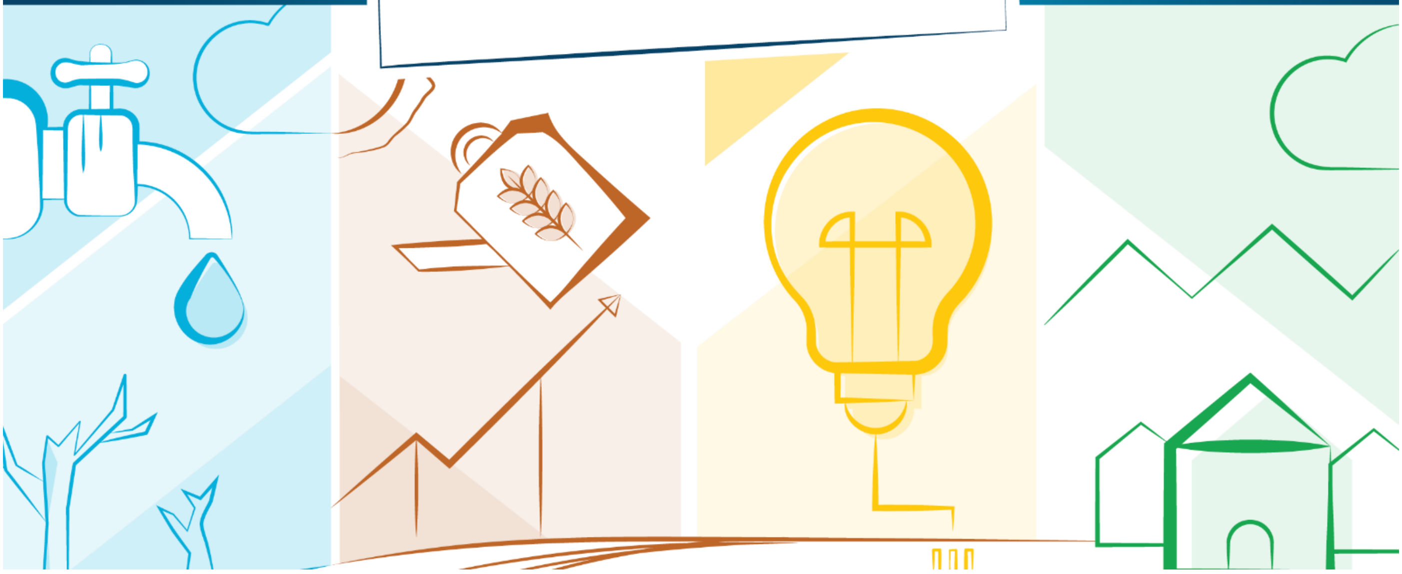

NEXUS-NESS

NEXUS NATURE ECOSYSTEM SOCIETY SOLUTION

Fair and sustainable resource allocation demonstrator of the multiple WEFE Nexus economic, social and environmental benefits for Mediterranean regions

GRANT AGREEMENT NUMBER 2042

Deliverable D4.1
Dynamic and spatially distributed modeling of WEFE Nexus
V1.1 30 November 2022

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WP4 Leader, Task 4.1 Leader: POLIMI, Maria Cristina Rulli and Task 4.2 Leader: SSSA, Rudy Rossetto

NEXUS-NESS - NEXUS NATURE ECOSYSTEM SOCIETY SOLUTION: FAIR AND SUSTAINABLE RESOURCE ALLOCATION DEMONSTRATOR OF THE MULTIPLE WEFE NEXUS ECONOMIC, SOCIAL AND ENVIRONMENTAL BENEFITS FOR MEDITERRANEAN REGIONS

GRANT AGREEMENT NUMBER 2042

Deliverable D4.1

Dynamic and spatially distributed modeling of WEFE Nexus

30 November 2022

WP4 Leader, Task 4.1 Leader: POLIMI, Maria Cristina Rulli and Task 4.2 Leader: SSSA, Rudy Rossetto

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Abstract	The deliverable reports on the actions taken in relation to T4.1 Agrohydrological model for WEFE Nexus and T4.2 NEL scale hydrological model and ecosystem service model. It introduces the role of the modeling tasks and tools in the project and the role of modeling in the Nexus in general. Then it reports on the data collection process, and the adaptations and expansions performed on the WATNEEDS model to suit it to the project aims. Introductory results are presented ad commented for the four Nexus Ecosystem Labs. Finally, the deliverable discusses actions taken in terms of internal and external communication and dissemination in regards to the modeling tasks and tools, and describes the present and future interactions of WP4 with the other work packages, with a specific focus on the flow of information.		
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1. Purpose of the Deliverable

The purpose of the deliverable is to illustrate the progress made in tailoring the modeling tools and competences of the WP4 partners to the NEXUS-NESS project instances. More specifically, this deliverable aims at reporting the actions taken under the first phase of Tasks 4.1 and 4.2. These tasks consist of the use of the WATNEEDS(Davide Danilo Chiarelli et al., 2020) and FREEWAT(Foglia et al., 2018) models, respectively, to provide scenarios of WEFE Nexus management. The first phase of these tasks consists therefore of the representation of the WEFE Nexus 'as-it-is', in order to provide a benchmark for the future development of the WEFE Nexus management plans, and a basis for a quantitative understanding of current challenges and potential solutions. After introducing how modeling plays a crucial role in the WEFE Nexus management framework, this deliverable presents the steps made to adapt both modeling tools to the scales, characteristics and challenges of the four Nexus Ecosystem Labs (NELs) and the results of these implementations in the current scenario. Then, it illustrates the ongoing model expansion work to better quantitatively capture the expected challenges and solutions from the NELs, and it details how this work will interact with the actions of other work packages to fulfil the project objectives.

1. Introduction

1.1 The role of models in WEFE Nexus management

The concept of Water-Energy-Food Nexus is intended to depict the complex interconnections between the different sectors of the resource system that provides livelihoods to the human population (FAO, 2014). The Nexus analytical lens helps identifying trade-offs, externalities and synergies in the assessment of complex problems involving the interactions among the economy, societies and ecosystems. With regard to the latter, the Ecosystem component has been recently included in the WEF, now WEFE, Nexus, so to better encompass the natural environment as an active role-player in the nexus rather than a passive context element. Among the issues that can be addressed with a Nexus approach, the management of natural resources surely is one of the most challenging and promising. This is not only because the management of natural resources is strictly related to the main theoretical concepts underlying the WEFE Nexus, but also because it is an extremely concrete issue, with near-immediate consequences on the everyday life of interested communities and the preservation of interested ecosystems. Applying the WEFE Nexus framing to the management of natural resources means developing management plans that explicitly account for complex interactions among the actions proposed to ensure availability of, and access to, water, food and energy, while also ensuring the protection of ecosystem services. As a consequence, Nexus management plans require an uncommonly high degree of complexity, as they have to analyse different resource system sectors in depth and at the same time consider them as organic and mutually interactive components of the same human-environment system. Therefore, the task of defining, evaluating and selecting proposals in a Nexus management plan is not a trivial one, as it has to be performed in a conscious way with respect to the multiple and multisectoral impacts of the proposed actions. Similarly, planning resource management from a Nexus lens makes it possible to identify solutions with synergistic cross-sectoral outcomes, enabling the implementation of more sustainable strategies. In this context, disposing of advanced modeling tools and skills becomes an effective asset to quantify impacts and outcomes of Nexus management plan proposals *before* their implementation, thus ensuring a more reliable and transparent evaluation and selection procedure. In essence, having a model base to support the development of Nexus management plans helps making decisions in an effectively and objectively informed way. This is also the key to understand why this modeling base is particularly important in participatory planning processes, even though this might seem a counterintuitive claim. Indeed, models are typically developed and implemented within the academic sector, thus resulting in a naturally top-down tool, in contrast with the bottom-up dynamic of participatory processes. However, in simple terms, models do no more than providing representations of phenomena starting from information and instructions provided by the user. This means that if information is provided, and questions are asked, by the stakeholders involved in the participatory process of the Nexus management plan development, the models become essentially a tool at the service of the involved communities. This holds as long as the models are made able to receive this information and answer to these questions, and the capabilities of the models are correctly communicated not only within the technical team involved in the management plan development, but also, and most importantly, to the stakeholders. In the following sections, the steps taken in these directions are illustrated.

1.2 Water as the modeling core of the WEFE Nexus

When addressing issues in a WEFE Nexus framework, it is important to keep a correct balance of primacies and relative importances of the Nexus components with respect to each other. The importance of the water component is often less tangible, and in some sense less governable, than for instance the food and energy components. However, for similar reasons, it is also often regarded as the central component when it comes to modeling the Nexus. Water has a primal role in many of the functional processes of the other components, for instance in the production of food through agriculture, in many forms of energy production and in the provision of ecosystem services. While similar interactions are evident also among other components, those involving water often have characteristics of (relatively high) transversality and (relatively low) complexity that make them well suited to be the modeling target in Nexus analyses. For instance, the water footprint framework can be applied both to the production of food and energy, and indicators can be derived to assess in these terms the impact of both sectors on the ecosystem. This is just an example of how water can be used to “translate” problems and potential solutions across sectors and Nexus components. The core of the modeling working package of Nexus NESS is therefore constituted of hydrological models, which are then enriched with specific add-ons that serve the purpose of making these models capable of “communicating”, i.e. exchanging information, either as input, output, or internal parameter, with non-water items of analysis. This “translation capability” is fundamental also to make Nexus interactions explicit, quantifiable, and thus communicable to the interacting work packages, to the NEL stakeholders, and to the community of practice. In a way, the communicability of components within the model is reflected by the communicability between the models and those who are supposed to interact and benefit from them. As a consequence, this is not only crucial for the models to be able to capture Nexus interactions, but also for their successful implementation in the challenges co-definition and solutions co-creation processes, where the transparency of the quantitative tools used is fundamental. Wrapping up, using water as the modeling core of the WEFE Nexus makes it possible to provide models that are simple enough to be flexible and transparent at the same time, and thus capable of quantitatively describing situations that might even go beyond their original modeling capabilities, thanks to the technical improvements by the scientific team and to the valuable knowledge coming from local experience.

1.3 Comparative introduction to the two NEXUS NESS modeling tools: WATNEEDS and FREEWAT

In regard to the importance of the modeling task, NEXUS NESS plans the application of two independent modeling tools, but with complementary features.

WATNEEDS (D.D. Chiarelli et al., 2020) is a spatially distributed agro-hydrological model that quantifies the water needed and used by plants during their growth. It combines climatic information with soil information and plant characteristics to simulate the plant growth in function of the soil moisture status in irrigated and rainfed conditions.

FREEWAT (Rossetto et al., 2018) (FREE and open-source software tools for WATer resource management) is a free and open source, QGIS- integrated modelling platform for planning and management of water resources, with a specific focus on groundwater.

The two models have the potential to work in combination with each other, both in sequence and in parallel, depending on the specific issued to be addressed. For instance, WATNEEDS can provide crop evapotranspiration demand to FREEWAT, and FREEWAT can feed WATNEEDS with the water available in the soil. The two models can also solve some specific tasks independently from each other, as they both arise as stand-alone applications. The decision of using one model or another will originate from a discussion among modelers and the NEL leaders, so to choose the modeling strategy that is most suited to address each of the specific issues emerged during the NEL workshops.

Deliverable 4.1 is based on the description of the as-it-is scenario at the NEL scale, for which WATNEEDS has been used. Thus, deliverable 4.1 is focused on the presentation of WATNEEDS, mainly used for the as-it-is scenario description, and on its arrangement to cope with the specific necessity of the NELs. FREEWAT is going to be then presented in deliverable 4.2, altogether with its applications.

A brief introduction on data collection, common to both models, will be presented, before the delving into the technical details of WATNEEDS, its adaptation to the project, and the first results.

2. Data collection

In the previous sections, we described how models can serve as participated management tools if the necessary information and the modeling questions are provided in a bottom-up direction. The NEL leaders guide the process of obtaining modeling questions within the activities of WP3, using the procedures defined in WP2. The fact that the modeling team is collaborating in the definition of modeling questions only through the mediation of the NEL leaders is important to prevent the risk that modeling choices are influenced by the knowledge of modeling capabilities, for instance by (even unwillingly) steering the process towards the identification of issues that are better quantifiable, but of lesser importance to the local stakeholders.
Instead, concerning the bottom-up collection of information, many of the data required are transversal with respect to the modeling question, many others derive directly from the modeling question once it is framed. Therefore, in most of the cases, the modeling team can autonomously make decisions on data requirements. In general, it is important to collect data locally, so to provide representations of the Nexus that are adequate and well suited to the case study. More specifically, the preferred source for modeling data is local data sources provided by public authorities, a combination that ensures both reliability of the data and protection of sensitive information. Data from government web portals (e.g. regional authorities, state agencies, ministries) are also a valuable data option, and are mostly freely available, even though finding the source can be a non-trivial operation for non-local users. Finally, when these two options are not available, global datasets are usually free to use and provided by the developers (e.g. in association to scientific papers or reports), although the scale of these data is clearly not optimal for the scope of the analysis. On the other hand, different types of data have different priorities because they have different levels of importance in the modeling process.

To proceed with the data collection while accounting for these different degrees of importance, a datasheet has been provided to the NEL Leaders, with a degree of priority and a short description associated to each requested data entry. While this datasheet was originally created for FREEWAT, it has been adapted to illustrate WATNEED's data requirements. In this case, the data requested with the highest priority were the extent of the study area, i.e. the boundaries of the NEL to be used in the simulations, and the spatially distributed information on the crops harvested in the NEL. Data requested with intermediate priority included land use, geology and pedology, data on the structure of the irrigation systems, and data on water demand. Data requested with low priority (i.e. data not necessary for the functioning of the model or data for which the default model input is of sufficient quality) include meteo-climate data, and other data from monitoring stations. The full list of data entries can be found directly in the datasheet, provided as an attachment to this deliverable.

3. WATNEEDS

WATNEEDS (D.D. Chiarelli et al., 2020) is a dynamic spatially distributed agro-hydrological model developed at Politecnico di Milano for assessing agricultural crop water demand and green and blue water. Green water can be defined as evapotranspired water that was available as precipitation-generated soil moisture. Blue water, conversely, is defined as evapostranspired (or consumed) water that has been withdrawn from surface or subsurface freshwater bodies. WATNEEDS can be run under different climate scenarios, crop distribution alternatives and spatial scales. The model has been largely used for estimating crop water demand, green and blue water, under different scenarios at the global and local scale. From this background derives WATNEEDS's potential to be used within the NEXUS NESS projects. The first objective is modelling the Nexus in the NELs, so to inform the Nexus managements plans. The second, longer term objective is the creation of a dashboard to demonstrate the interaction of the Nexus in a user friendly, interactive way (Task 4.3).

In the next paragraphs we first present the WATNEEDS model and its potential at the time of the project start. Then we describe the adaptations that have been done in order to make WATNEEDS suitable to describe the NEL challenges. The results for the current scenario are presented in form of temporal and spatial variations in crop-specific water use, as produced by the adapted model. Finally, we present the model expansions that have been designed and developed in preparation of the next phases of the projects, with the aim to move from hydrological modeling to Nexus modeling, and so to tackle the NEL challenges and evaluate the NEL solutions, once the co-definition and co-design processes have transformed these challenges and solutions in instances that can be synthetized into model forcings. These expansions include, for instance, energy calculations for irrigation, crucial for including the energy component of the Nexus, and agrivoltaics.

3.1 Model presentation

WATNEEDS models the vertical soil water balance in the soil active layer, i.e. the layer of the soil where plant roots are able to uptake water. It does so by combining meteorological data with quantitative characteristics of the soil and crop-specific parameters, to solve the water balance equation at the daily time scale. More specifically, precipitation is the main climatic forcing, which is then transformed in effective precipitation by subtracting, when present, the fraction of precipitation that does not reach the soil (e.g, because it is abstracted by vegetative cover or because it transforms directly into surface runoff). Soil parameters are used to determine the maximum amount of water the soil active layer can retain and the maximum velocity by which water can percolate towards deeper soil layers, and thus, as applicable, to determine the excess water that contributes to surface runoff. The potential evapotranspiration is used in the form calculated by the FAO Penman-Monteith equation(Allen et al., 1998), thus depending on a set of meteorological parameters such as solar radiation, wind speed, relative humidity, temperature and cloud cover. This potential evapotranspiration is combined with crop coefficients, depending on the crop growing stages, to obtain the daily water demand of each crop. The root depth is used to determine the actual depth of the soil active layer, while the depletion factor informs the model on how much of this depth the plant is able to use before entering into stress conditions. In this way, the model is able to calculate, at a daily time scale, how much of its water demand a cropped surface is able to withdraw from the precipitation water that has been stored in the soil active layer, and the remaining part that the farmer may supply by irrigation. These two fluxes are defined respectively as green water and blue water and are the main model outputs. Besides these outputs, the model is able, depending on the selected simulation mode, to return information on all the main fluxes involved in the balance. In its original form, i.e. at the beginning of the NEXUS NESS project, WATNEEDS was able to compute this balance at a resolution of 5arc minutes (slightly less than 10km at the equator, progressively reducing with latitude) for 23 crops and 3 crop groups, with planting and harvesting dates as provided by (Siebert and Doll, 2010.). It used maps that, for each of the pixels of 5arc minutes per side, contained the data on how many hectares of each crop are expected to be cultivated in that pixel. This means that crop specific outputs are created at 5arc minutes resolutions but are relative to the fraction of the pixel that is cultivated with that specific crop, while cumulative (site-specific, but not crop specific) outputs are relative to the pixel-specific crop mix.

The application of WATNEEDS to the NELs starts from combining the quantifications of green and blue water simulation data with real data, instances and specifications produced by the participatory processes undertaken in the NELs. A very simple example can be the combination of green and blue water with information on which crops are irrigated and which not, to evaluate which crops are provided with blue water and which crops are being sustained by green water only. Examples of increasing complexity can include the use of locally sourced crop yield data in combination with model simulations to compute actual and expected yield gaps, or the combination of blue water data with information on the irrigation systems to compute the energy demand for irrigation. All these applications, including the simplest one, require the model to be tailored to the case study, i.e. the NEL. This is not only important to ensure the correct unfolding of the transformative process in the NELs, but also, from a more technical point of view, because simulations produced with a case-study tailored resolution have a higher quality, and because the combination of simulated and locally sourced data is more reliable and coherent if also the simulated results derive, at least partially, from locally sourced data. This is why the main adaptations of the model focused on making it ductile in terms of spatial resolution and of input data.

3.2 Model adaptations to tackle the NEL challenges

The need for model adaptations to tackle the NEL challenges stems from the necessity of modeling tools able to capture the specificities of the single NELs and their intra-NEL variabilities. Moreover, in view of the provision of the interactive dashboard, the model must be at the same time capable of addressing challenges and solutions in a scale- and context-adaptive way, so that quantitative analyses and comparisons can be made not only within the single NELs, but also across NELs and at a wider, quasi Euro-Mediterranean scale.

The first adaptation made to the model has been to make it ductile with respect to the spatial resolution. This means, while the original WATNEEDS version worked on a fixed 5arc-minute resolution grid, regardless of the extent of the analysis, which was either global or country-specific, in the new version of WATNEEDS the grid is provided by the user. Therefore, both the spatial resolution and the extent of the analysis are user defined. This allows the user to run the model on the specific area of interest (e.g., the NEL) with the pixel size that best combines the resolutions of the input data and best fits the trade-off between quality of the outputs and computational time. From the physical point of view, this adaptation does not present significant hurdles. In fact, the soil water balance is performed in terms of water height (mm), also referred to as volume per unit area. Thus, the results of the model are independent of the extent of the “field” and, by extension, on the pixel size, once all the input data are set. The most significant hurdles are instead computational, and are those typical of transforming fixed parameters of an algorithm into variable ones. More specifically, the model has made been able to recognize the spatial information associated with the input data, which was not necessary in the original version, since both the extent and the spatial resolution were defined *a priori* within the model.

The second adaptation made to the model has been to make it ductile with respect to the crop distribution data. This was of particular importance, first because the default crop data used by WATNEEDS are at a 5arc-minute resolution which is too coarse to capture intra-NEL variability, especially for the smaller NELs, but also because at least in some NELs there is the necessity to model crops that are not included in the default crop dataset, and that must therefore be inserted *ex novo* in the model. Again, the best option, also in view of the dashboard, was to transform these fixed parameters in a set of inputs provided by the users, so that the model can work for whichever crop mix is provided. The inputs are provided in the form of crop-specific maps, with the same resolution and extent of the study area, and a table containing, for each crop, the necessary parameters, i.e. crop coefficients, relative durations of the growing stages, root depth and depletion fraction. The crop parameters are directly read by the model from the table. Instead, a model subroutine combines the spatial data from the map with user-provided information on the planting and harvesting dates and transforms them in the format needed by the model. Still, the crop maps have to be provided in a WATNEEDS-friendly format, i.e. maps with the same resolution and extent of the study area (and therefore, the same number of rows, columns and non-void pixels), representing, for each pixel, the area cultivated with a specific crop, in hectares. A possible improvement might be the design of a tool that, given a crop distribution map, automatically transforms extent, resolution, and data format to match WATNEEDS's requirements, but for the moment, given that crop distribution maps come in a wide range of formats, leaving this operation to the user seemed the best option. The fact that many NEL-specific data had to be custom required, and thus had the possibility to be delivered directly in the required format also contributed to this choice.

The third adaptation is less related to the data processing stage and more to the physical core of the model. While the model was initially ideated for the assessment of blue water, as the difference between the crop water requirements and the available green water stored in the soi, we made efforts to simulate the soil moisture variation under different irrigation applications. In this latter case, we loosen the concept of green and blue water, but we can better predict the moment in which irrigation is needed and its quantity.

Some minor adaptations were made, for instance, to increase the resolution of other input data. In fact, by increasing the modeling resolution and using locally sourced, and thus more high quality, parameters, other input data that were of sufficient quality in the original version of WATNEEDS risked to become a limiting factor in the new version's output quality. One of these input data was the potential evapotranspiration, which was retrieved, in the original version, from (ref.), at a resolution of 0.5degrees. It is now retrieved from (ref.) at a resolution of xxx. Similar modifications have been made to the soil parameters, specifically the maximum retention capacity and maximum infiltration rate. Depending on the modelling questions from the NEL, and the availability of additional data, further similar modifications will be possible, to push towards higher quality representations of specific processes or variations.

3.3 Results

The as-it-is scenario has been run for the 4 NELS. For each NEL the amount of green and blue water has been computed according to the data provided by the NEL leader. Knowing the current status in the use of natural resources and the grand challenge identified by each NEL, it is possible to provide and analyze different alternatives toward a more sustainable and resilient future.

3.3.1 Spain

The Spanish NEL is composed by two subzones of the Duero basin: the Cega-Eresma-Adaja and the Bajo Duero, also named Tordesillas-Toro (see D3.1, booklet 2). The two main crops harvested in the Spanish NEL are wheat and barley: as per the data provided by the NEL, the area harvested with barley and wheat are about 255’700 and 224’000 hectares respectively. In both cases, roughly 90% of the area is rainfed. Among the main irrigated crops, maize, potatoes, and sugar beets account for 15’400, 8’000 and 7’400 hectares respectively. In addition to these areas, some 1’700, 610 and 440 hectares of the same crops result to be cultivated in rainfed conditions. These five crops, for which the results of the hydrological model are presented, account for 76% of the total agricultural area in the NEL. A variety of crops is cultivated in the remaining 25%. Among these, sunflower and vineyards are the most common, followed by several different minor cereals, tree crops, horticultural crops and legumes. Although the five selected main crops are sufficiently diffused in the region to provide a reliable general picture of the main agro-hydrological features of the basin, the whole variety of crops cultivated in the region entails not only technical, but also economic and even socio-cultural aspects that will have to be considered in the next modeling steps. The results are presented in the form of maps and charts, to provide visualizations of both spatial and temporal trends of water use by crops in the basin.
Figure 1 shows the typical output of the WATNEEDS model: a raster map with the same resolution as the processing resolution set for the model (in this case, 15 arc seconds, around 450m at the equator), with the information in the pixel (i.e., the color code) is a millimetric water flux. In the specific case of Figure 1, it is the green water used by the fields of the two main rainfed crops in the NEL, namely wheat and barley. What first emerges is that barley is slightly less water intensive than wheat. In particular, wheat consumes slightly

more green water than barley in the same locations. This can be partly due to the longer growing period of wheat with respect to barley: wheat is planted in December, while barley in February, and both are harvested in July. Moreover, wheat has slightly higher crop coefficient values in the initial and final stages of the growth period than barley, which, for the same weather/climate (e.g., for the same locations) renders slightly higher potential evapotranspiration values. The result is that these differences in water use between wheat and barley are more evident in places where water is more abundant, and thus less a limiting factor for the crop growth, as for instance in the hilly regions in the NEL's Southeast. Conversely, in the lower portion of the basin, in the Northwest, water uses are lower and more similar to each other. The interpretation for this can be that crop water use in that area is limited by water availability, and thus by rainfall, which, for the same location, is virtually the same for both crops.

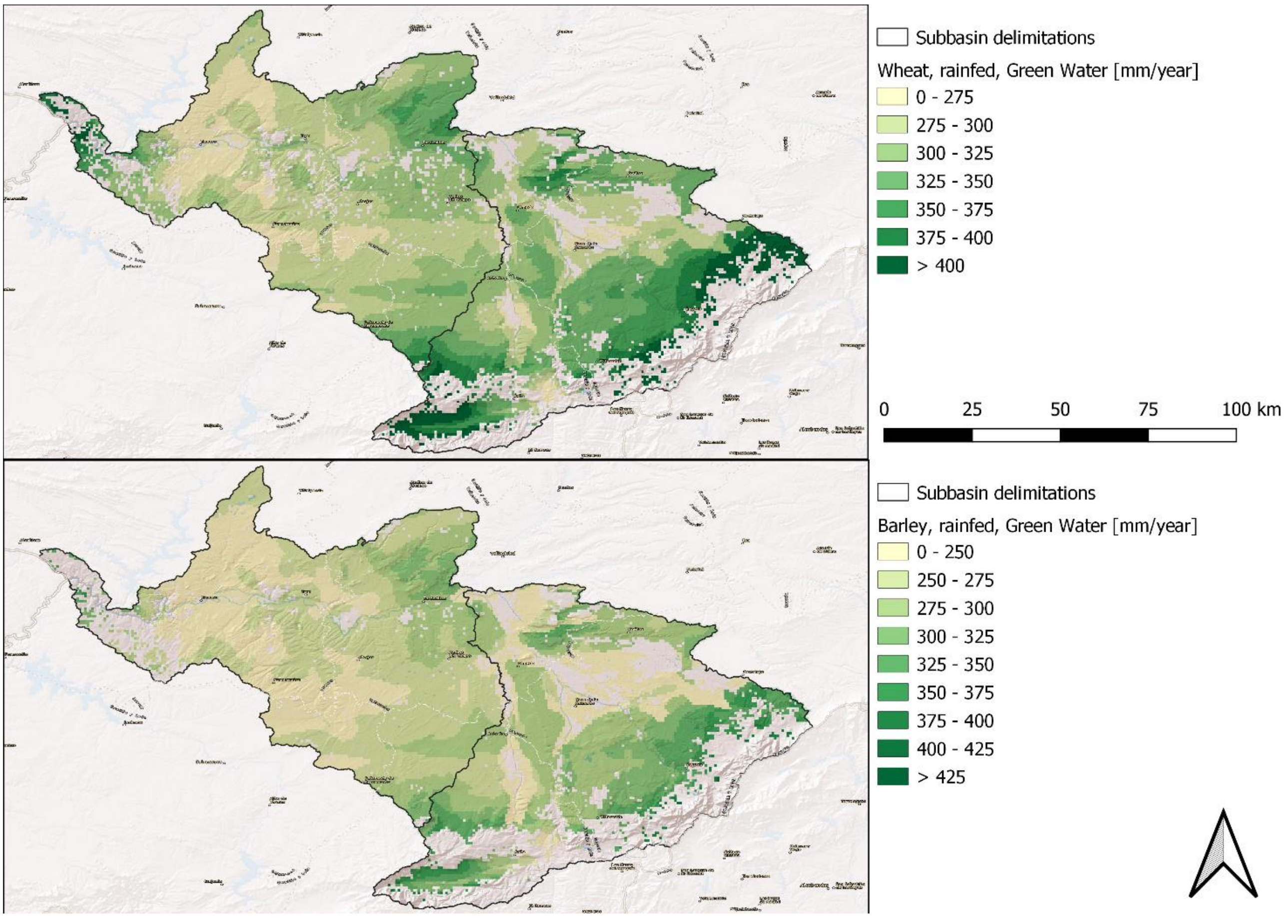

Figure 1 Map of yearly green water use of the 2 main rainfed crops in the Spanish NEL, for the average year 2016-2021

Similar considerations can be drawn from the observation of water use maps for irrigated crops, reported here for maize in Figure 2. In this case, in addition to green water, blue water is also computed. For the results of this Deliverable, blue water is computed in the consumptive form, i.e. as the difference between crop water requirement and green water, thus representing the share of crop water requirement the plant is not able to satisfy by direct abstraction from the soil moisture, and thus must be provided by irrigation if stress is to be avoided. This share represents a high proportion of the requirement of maize throughout the NEL, as can be seen from Figure 2. Green water values range mostly from 150mm to 250mm, while blue water values vary from around 400mm to more than 500mm. This is partly due to the model assumption that sets the threshold for irrigation at the maximum allowable depletion. Below this level of soil humidity, the plant enters in stress conditions, but is still able to withdraw water from the soil. Therefore, green water for rainfed maize in the same locations would be slightly higher. However, the values of green water for maize are similar to those reported in Figure 1 for rainfed crops in the same locations. Therefore, it is likely that also in this case water availability is the main limiting factor. This can also be seen in terms of local differences of green-blue water repartition within the NEL (Figure 2). For instance, the area in the Northwest with the lowest green water use is the one with the highest blue water use. Conversely, areas in the Southeast with higher green water uses have lower blue water values. This is because, the crop water requirement depends on weather-climate conditions such as temperature and solar radiation, that tend to have lower spatial gradients than precipitation, the key determinant in the repartition between green water and blue water. As a consequence, local variations in green water are similar and opposite to the local variations in blue water, since they sum up to the crop water requirement, which is has less spatial variability.

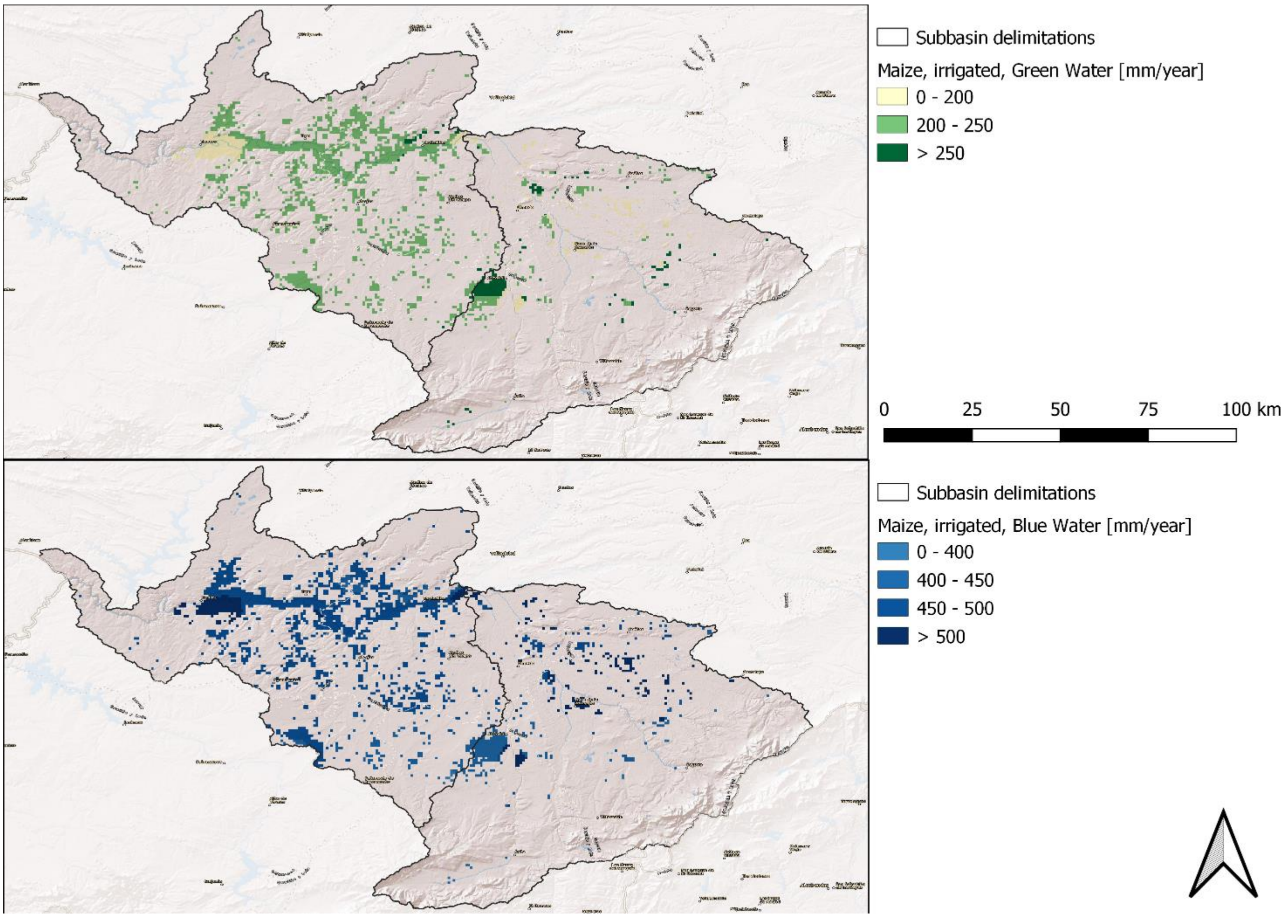

Figure 2 Map of the yearly green water use and blue water requirement of maize in the Spanish NEL, for the average year 2016-2021

All the considerations derived from Figure 1 and Figure 2 are specific to the behaviour of the single crop, depending on the location, because the data have been presented in form of water height, i.e. volume per unit surface. The importance at the NEL level of the one or the other crop in terms of water use can be better understood when the total volumes are computed, thus accounting for spatial variations not only in water intensity but also in harvested areas. We show these values and their seasonal variations in Figure 3, Figure 4 and Figure 5.

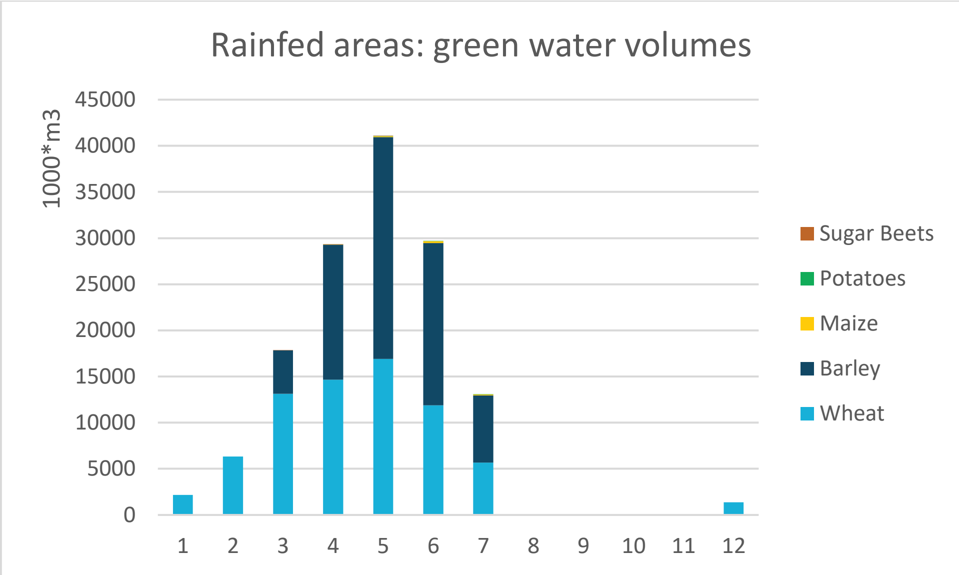

Figure 3 Monthly values of volumetric green water requirements for five main rainfed crops in the Spanish NEL, for the average year 2016-2021

Figure 3 shows the seasonal variations in green water requirements for the rainfed areas of the 5 main crops listed above. The values are in cubic meters, therefore they account both for the crop- and site-specific demand and the extent by which each crop is cultivated. Therefore, expectably, barley and wheat account for the lion's share of green water volumes. Millimetric water requirements may be lower for these crops than for the other ones, but it is exactly this that makes rainfed harvesting convenient for these crops, as they are less likely to get into water stress than other crops, and thus they are much more diffused in rainfed conditions. Nonetheless, wheat and barley also show relevant figures in the green water volumes for irrigated areas (Figure 4). In fact, even though the irrigated areas for wheat and barley are only one tenth of their respective totals, they still are comparable with the irrigated areas of the main irrigated crops. Still, the contributions of traditionally irrigated crops, in particular of maize and sugar beets, are well visible in Figure 4.

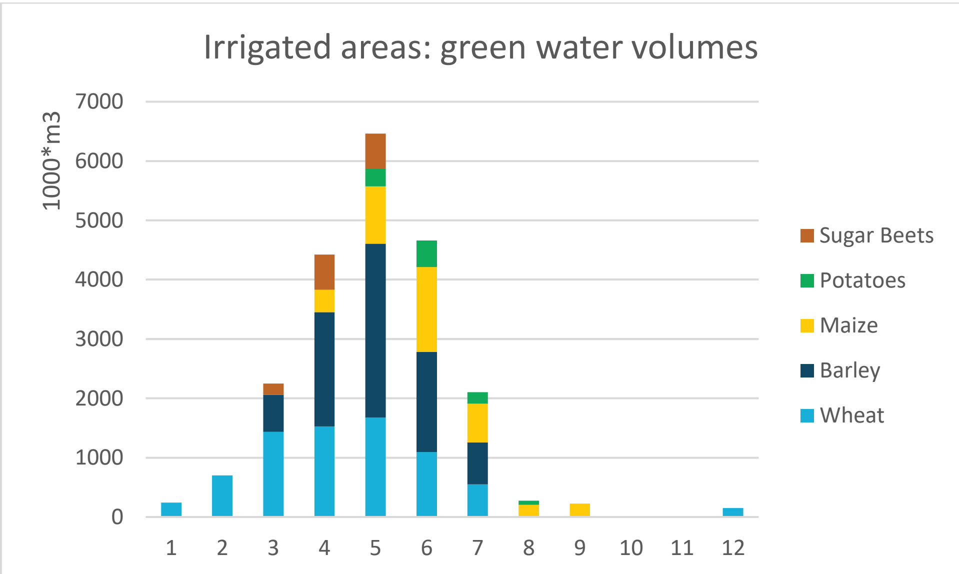

Figure 4 Monthly values of volumetric green water requirements for five main irrigated crops in the Spanish NEL, for the average year 2016-2021

It is also interesting to notice that the temporal trends of green water requirements are similar across rainfed crops and across irrigated crops, while, in general, irrigated crops present a peak of demand around June, thus with a slight delay with respect to the demand peak of rainfed crops, which is around May. All these aspects (crop-specific contributions as well as temporal trends) are even more visible in Figure 5, where crop-specific blue water demands are presented. The delay is even more evident because barley and wheat are modeled to be harvested in July, so after that month they have no water requirements, either green or blue. Conversely, potatoes and maize are harvested later, so their blue water demand lasts longer. Moreover, looking specifically at July, August, and, to some extent, September, we can notice that the blue water requirements (Figure 5) for these crops are much higher than green water requirements (Figure 4). This is due to the fact that these crops reach their highest development phase, and thus their most water-consuming phase, during the driest months of the year. As a consequence, most of the crop water requirement has to be supplied by irrigation, because green water is scarce in that period.

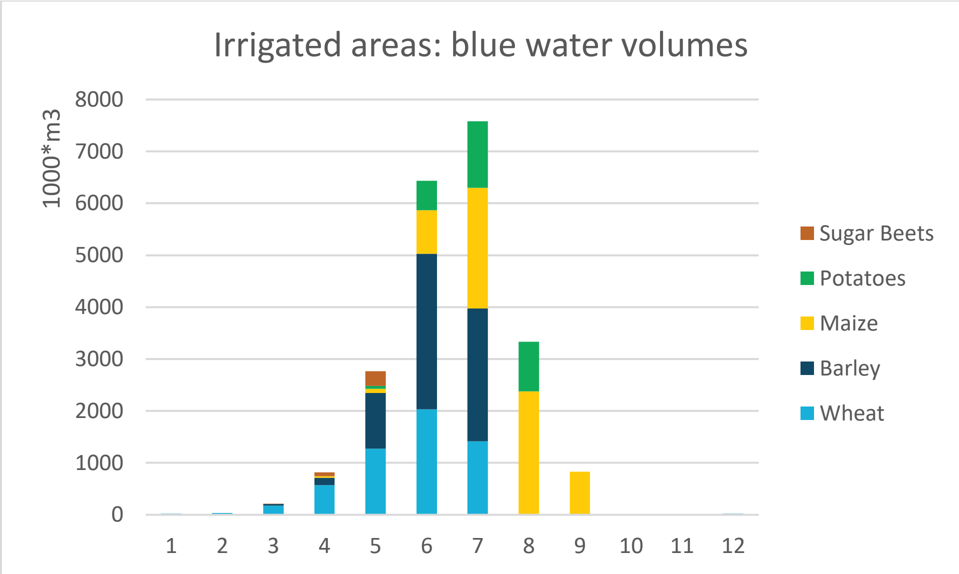

Figure 5 Monthly values of volumetric blue water requirements for five main irrigated crops in the Spanish NEL, for the average year 2016-2021

3.3.2 Italy

The Italian NEL includes the Cornia River basin and plain, in southern Tuscany. The upper part of the NEL corresponds to the Cornia watershed, while the lower part includes a coastal plain. The coastal plain is the area where most of the agricultural activities take place (see D3.1, booklet 1). Figure 6 shows the high diversity of crops grown in the NEL. Similarly to what happens in the Spanish NEL, in the Italian NEL a relatively small set of major crops is sided by a variety of minor, mostly horticultural crops, many of them with strong cultural heritage in the region. Durum wheat, sunflower and olives can be considered as the major crops, with 8690, 4851 and 3779 hectares respectively. Melons, grapes and artichokes follow up with 1607, 1112 and 925 hectares, respectively. We consider these crops, with the addition of barley, for the results presented in this deliverable, as they represent together more than 75% of the harvested areas in the NEL, and they are also representative of the NEL's agricultural diversity. Wheat, barley and sunflower are rainfed in the region, while melons and artichokes are irrigated. Concerning olives and grapes, farmers started to perform the so-called "emergency-irrigation", in case of excessive water stress/heat during late spring/the summer season. We assume that some irrigation practice exists for these crops, at least to some degree or, especially for grapes, and thus we present them as irrigated. Looking at rainfed crops first, Figure 7 shows the water use of wheat, barley and sunflower. Wheat and barley have very similar seasonalities, as they are very similar plants with the same cropping calendar. Sunflower instead grows during the summer season and it seems to present a strong resistance to water scarcity. In fact, the green water use for June exceeds 100mm, which is seldomly done by crops present in June in the same region. Since green water is naturally limited by availability, this denotes a high capacity of this plant to withdraw water from the soil.

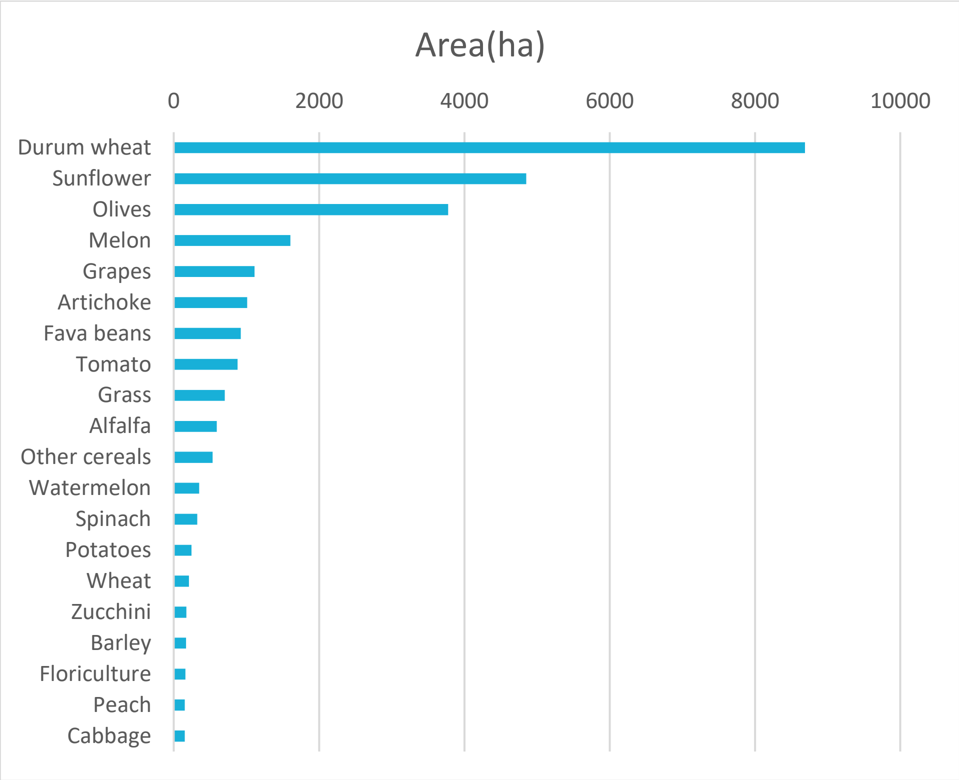

Figure 6 Total harvested areas of the main crops (>150ha) in the Italian NEL.

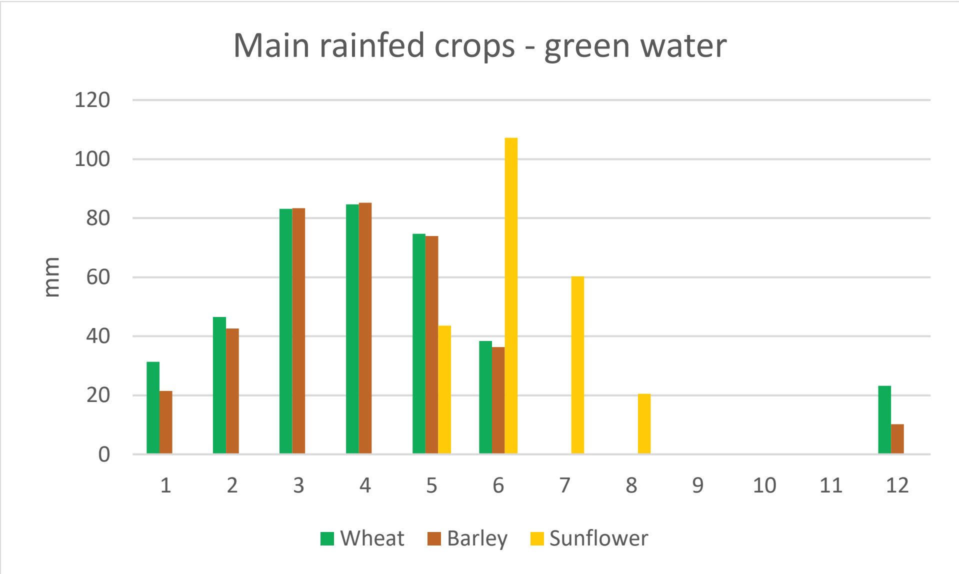

Figure 7 Monthly millimetric green water use for the main rainfed crops in the Italian NEL, for the average year 2016-2021.

Looking at the seasonality of irrigated crops (Figure 8 to Figure 11), most of the blue water requirements concentrate in the summer months (June to September), in accordance with the climatic conditions of the NEL. In particular, we see a similar behaviour for the two perennial crops considered, olives (Figure 8) and grapes (Figure 10), that have a peak demand in blue water that is delayed by 3 months with respect to the peak in green water use and by 1 month with the peak in crop water requirement (the total water demand, represented by the full height of the column). In any case, the demand in blue water arises in the final development stage of the plant, thus supporting emergency irrigation as the most likely and sensbile irrigation practice for these crops. Instead, the annual crops, namely melons (Figure 9) and artichokes (Figure 11) present their highest blue water need at the end and at the beginning of their life cycle, respectively. Moreover, they present peaks where the blue water represents a high share of the crop water requirement, and the relatively short duration of the growing periods makes these deficits relatively important also in time. All these elements make these crops more highly dependent on irrigation than the two perennial crops considered. In fact, while for olives and grapes there does not seem to be a common, recurrent irrigation practice, for melons and artichokes it is well known that the typical harvesting system includes drip irrigation, an irrigation system mostly used for high value crops such as the ones considered here.

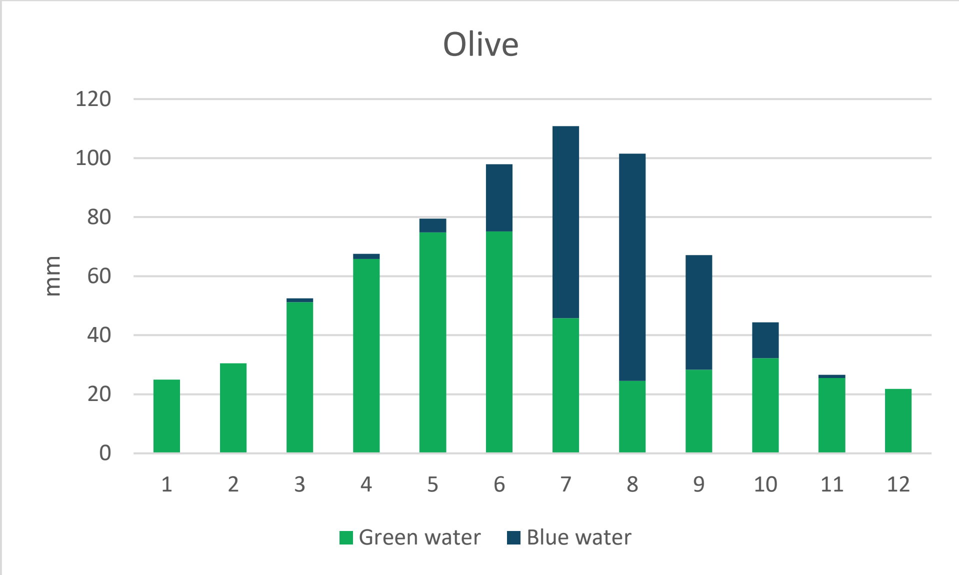

Figure 8 Monthly millimetric green water use and blue water requirement for olives in the Italian NEL, for the average year 2016-2021.

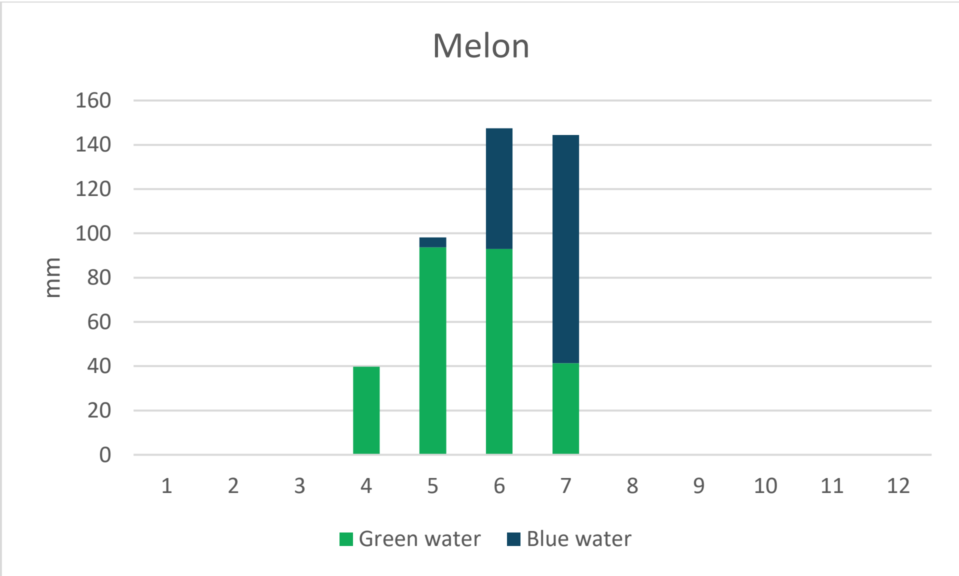

Figure 9 Monthly millimetric green water use and blue water requirement for melon in the Italian NEL, for the average year 2016-2021.

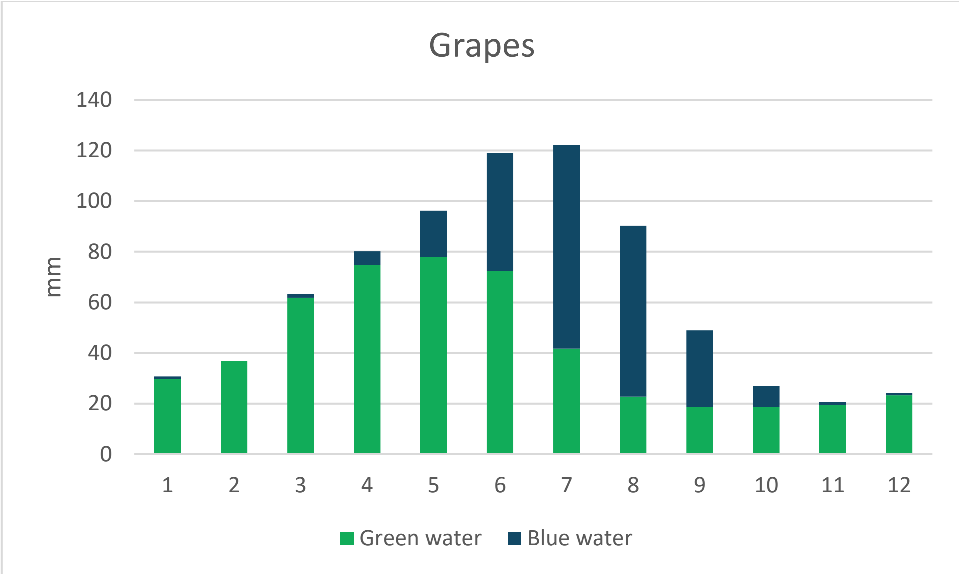

Figure 10 Monthly millimetric green water use and blue water requirement for grapes in the Italian NEL, for the average year 2016-2021.

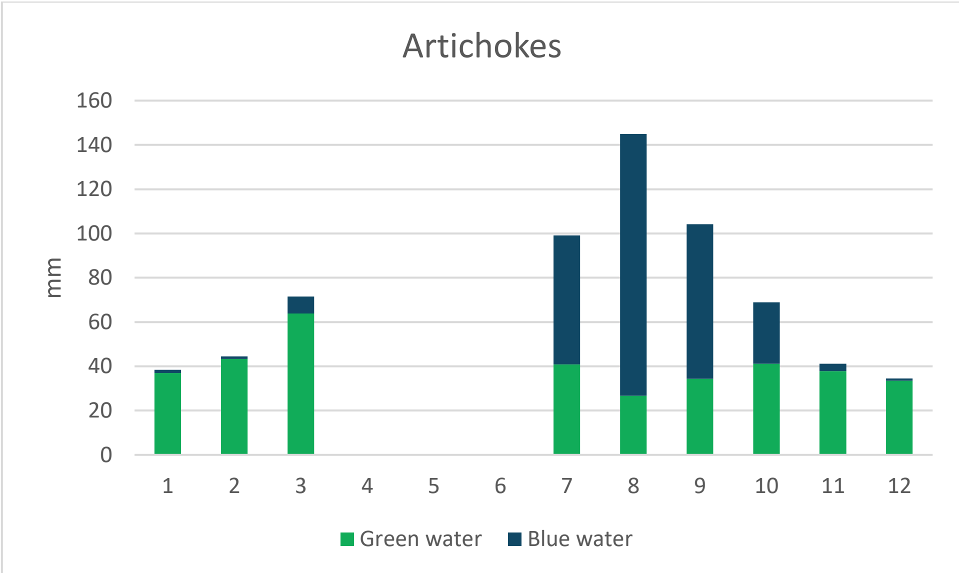

Figure 11 Monthly millimetric green water use and blue water requirement for artichokes in the Italian NEL, for the average year 2016-2021.

3.3.3 Tunisia

The Tunisian NEL is located in the Wadi Jir basin, in the Southeast of the country. The main crop harvested in the Wadi Jir basin, as from the data provided by the NEL, is olive, with more than 2750 hectares, followed by eucalyptus, which is harvested in a plantation of about 17 hectares in the Southwest area, close to Techine (see D3.1, booklet 3). The average annual green and blue water demand for olive is of about 200mm and 800mm respectively, and of 230mm and 1190mm for eucalyptus (Figure 12). While for eucalyptus there are no significant spatial variations, as the cultivation is entirely concentrated in the same location, water requirements for olive fields present some interesting features. There are some similarities between green water and blue water, as both tend to have higher values in the southern part of the NEL. However, these similarities are only partial ones. For instance, the westernmost part of the NEL has the highest green water values, while it ranks lower for blue water. A set of possible cases can be inferred from these similarities and differences if we keep in mind that green water and blue water are calculated to sum up to the crop water requirement. When both green and blue water increase, it means that the crop water requirement is also increasing, and this means that the meteorological conditions are different (e.g., higher temperatures, less humidity, stronger wind). This fits the presence of more water-intensive olive fields in the South. Instead, when the two components change in opposite direction, a difference in terms of precipitation is more likely: the crop water requirements are similar, but rainier areas can satisfy a larger part of it with green water.

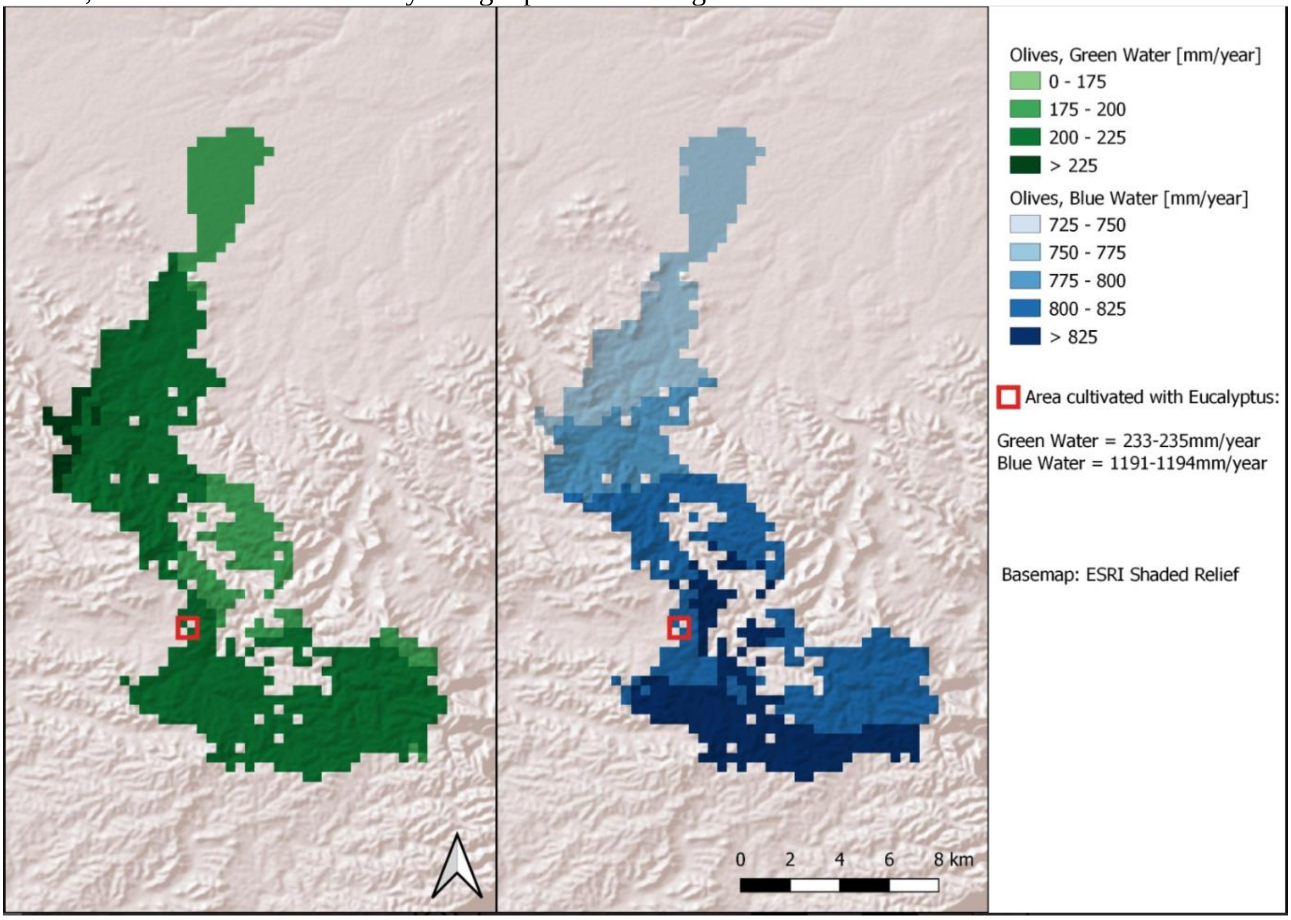

Figure 12 Yearly green water use and blue water requirement of olives in the Tunisian NEL. Results for the eucalyptus plantation are also provided in the map legend. Data refer to the average year 2016-2021.

In any case, the entire harvested area is under green water scarcity conditions, with precipitation being able to meet only about 25% and 20% of the crop water demand of olives and eucalyptus, respectively. The worse situation is registered during the summer, when the precipitation is virtually absent, but the plants require the most water. In fact, as can be seen from Figure 13 and Figure 14, the total crop water requirement has a typical oscillatory trend, with summer values doubling the winter values. The green water portion of the requirement is low throughout the year, but it gets almost null in July, August and September, while June and July are the months with the highest crop water requirement. This represents a persistent condition of green water scarcity that reaches severe degrees of intensity for at least two consecutive months in a year. Scaling this up to the NEL, the total volume of blue water required is estimated to be 217million m3 for olives and 40000m3 for eucalyptus. Clearly, with yearly rainfall rates ranging around 200mm, the fraction of this blue water volume that can be effectively provided by irrigation is constrained by water availability.

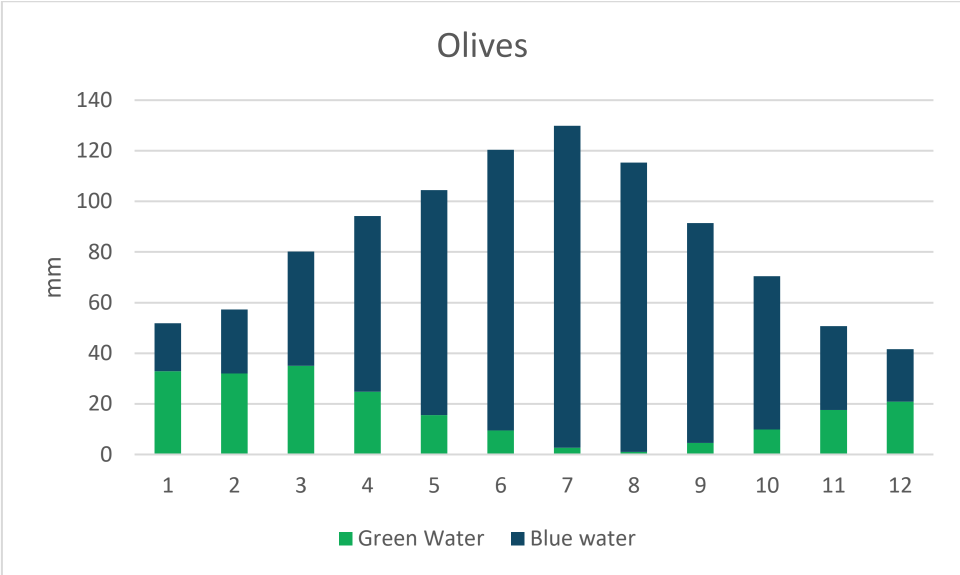

Figure 13 Monthly millimetric green water use and blue water requirement for olives in the Tunisian NEL, for the average year 2016-2021

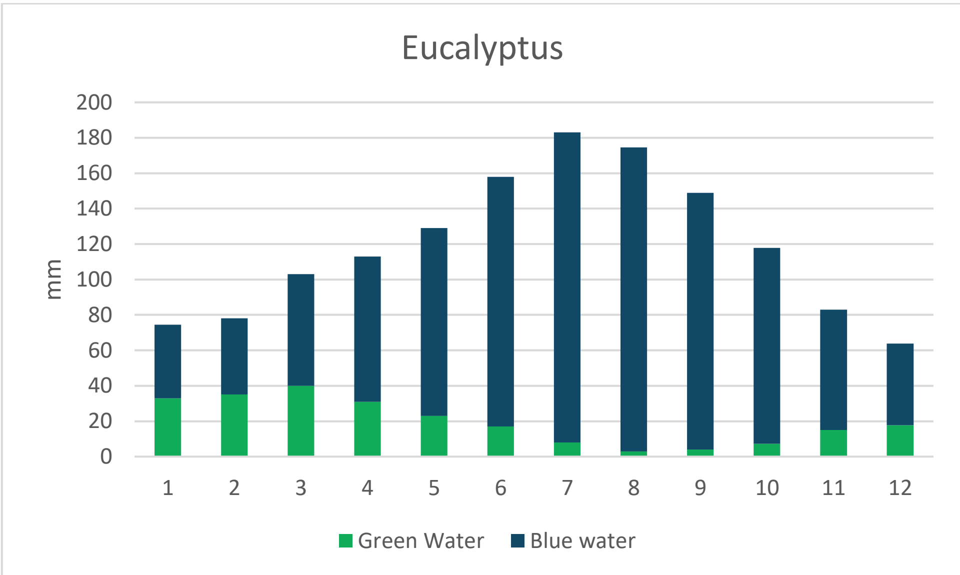

Figure 14 Monthly millimetric green water use and blue water requirement for eucalyptus in the Tunisian NEL, for the average year 2016-2021

The presence of a floodwater diversion system and the implementation of several water harvesting techniques provide a partial rebalancing of temporal and spatial mismatches between water demand and availability. Yet, in a situation of physical water scarcity as it is the case here, the irrigation of the fields in proximity of these infrastructures may reduce or preclude the possibility to use the water in more downstream areas, thus affecting the crop production. The main irrigation scheme in the Tunisian NEL is a spreading perimeter, connected to the floodwater diversion at the basin outlet. On one hand, the fact that it is collocated at the outlet prevents downstream effects that would have been way more intense if such a scheme were located in an upstream zone of the basin, and it allows to capture the most excess runoff. On the other hand, it makes the irrigation scheme dependent on the utilization and performances of all the upstream water harvesting systems.

3.3.4 Egypt

The Egyptian NEL is located in the Wadi Nagamish basin, close to Marsa Matrouh, in the Northwest of the country. The main harvested crops in the NEL are barley and tree crops such as figs and olives. Wheat is also harvested on a small scale, for experimental purposes. Tree crops are harvested over 135 hectares, spanning mostly in the lowlands formed by the course of the Wadi (Figure 15 and Figure 16). Instead, the 1323 hectares harvested with barley are more evenly distributed across the NEL (Figure 17). Yet, D3.1 – booklet 4 mentions 800 feddans, equal to 336ha, planted with barley. We choose to model 1323 hectares of barley because this information is spatialized, but this discrepancy within NEL data is part of the issues we aim at addressing immediately after the provision of this deliverable. The area has extremely low rainfall rates, and this reflects in the green water consumption of the crops in the NEL, which is severely limited by water availability. As can be seen from Figure 15, yearly green water use in fig plantations ranges between roughly 130 and 150mm, while blue water requirements are more or less five times as much. The fact that this is a water availability-limited pattern is also evident from the spatial distribution of these values, with higher blue water values occurring systematically in locations of lower green water use, and vice versa. Similar considerations can be made for Figure 16, showing analogous results for olives. By comparing the two figures, it can be noticed that while the green water ranges across similar values for olives and figs, while olives have uniformly slightly (around 50mm) higher values of blue water than figs. In generally, green water appears to be more available in the more upstream zones of the basin, and this holds also for barley (Figure 17).

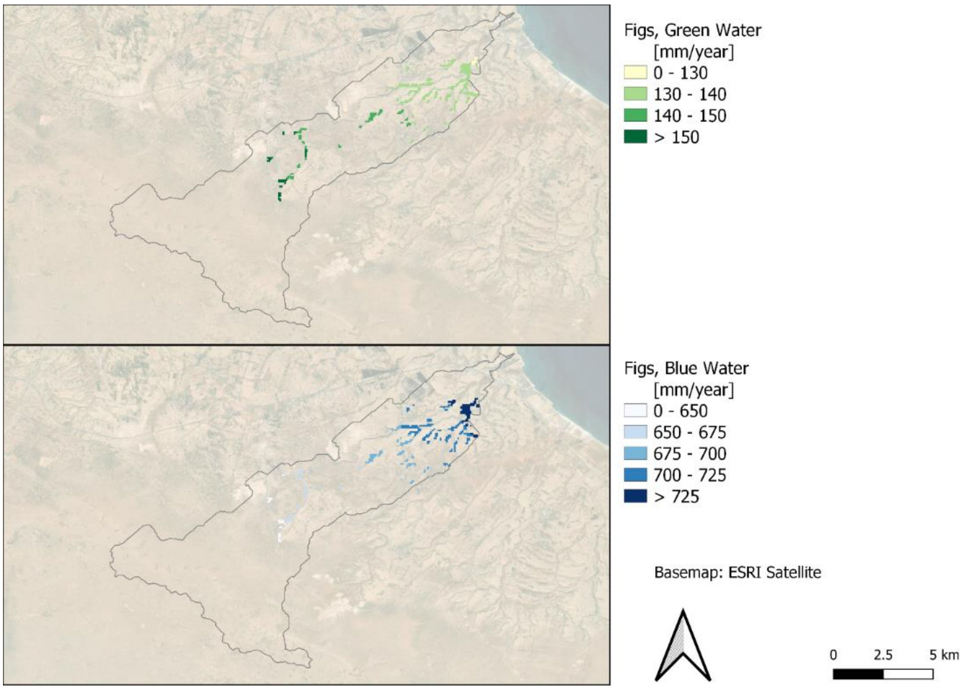

Figure 15. Yearly green water use and blue water requirement of figs in the Egyptian NEL. Data refer to the average year 2011-2016.

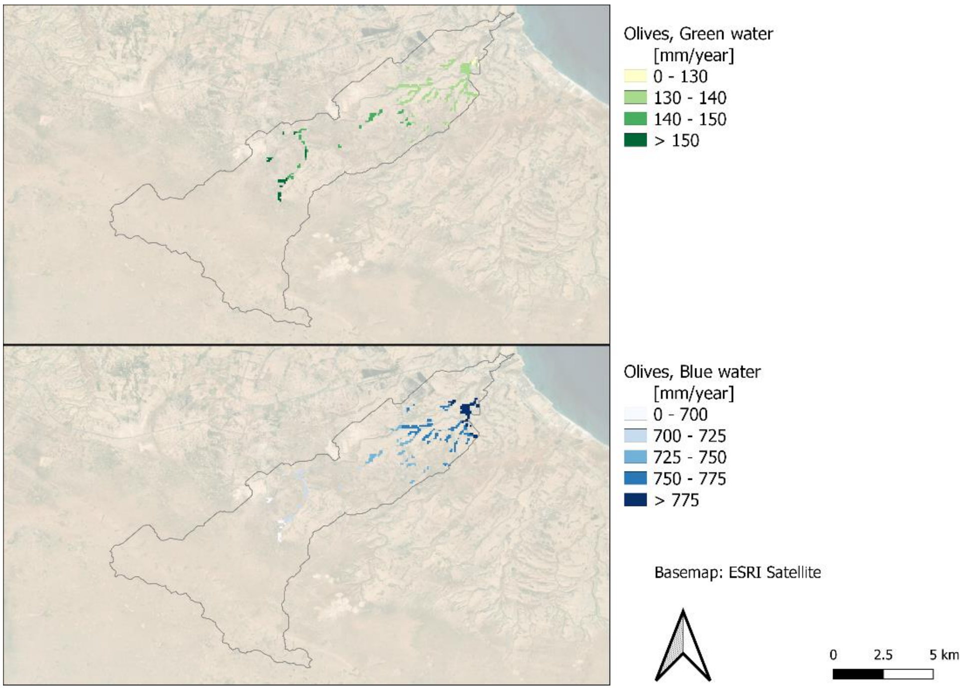

Figure 16 Yearly green water use and blue water requirement of olives in the Egyptian NEL. Data refer to the average year 2011-2016.

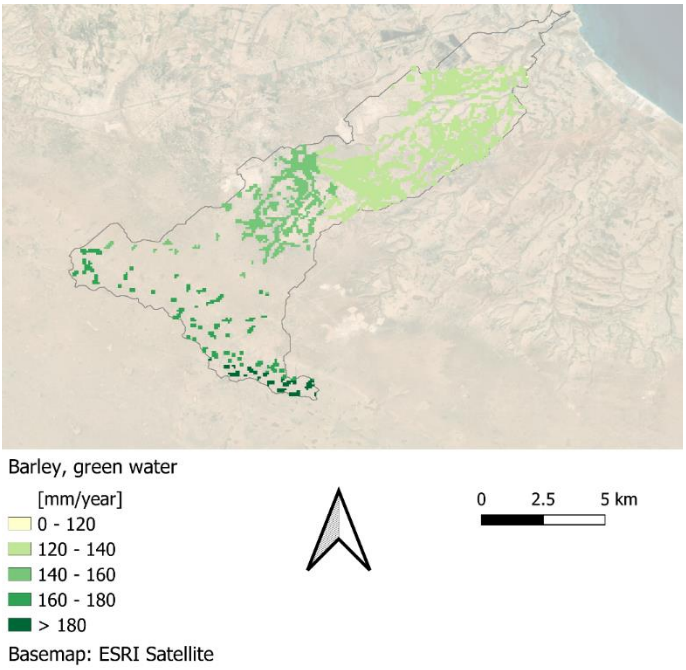

Figure 17 Yearly green water use of barley in the Egyptian NEL. Data refer to the average year 2011-2016.

As regards the seasonal variations, Figure 18 and Figure 19 show that, as it is typical for perennial crops in these climates, the highest crop water requirements occur in the lowest water availability months. In this case, we have July and August with no rainfall, and June and September with negligible green water heights. Comparing the seasonality of the two crops in Figure 18 and Figure 19, we can add detail to the information derived by comparing the two maps (Figure 15 and Figure 16). For instance, we see that the green water use trend across the year is practically identical between the two crops. This is because the availability of soil moisture is theoretically the same, with only some slight differences in the abilities of the plants to uptake it. The blue water demand presents some more interesting differences, with figs requiring slightly less blue water in the summer months and slightly more towards the end of the year. This means that figs not only require less water during the year than olives, but they also do so by better following the regional rainfall pattern. However, this happens in a context of high green water scarcity that affects both figs and olives.

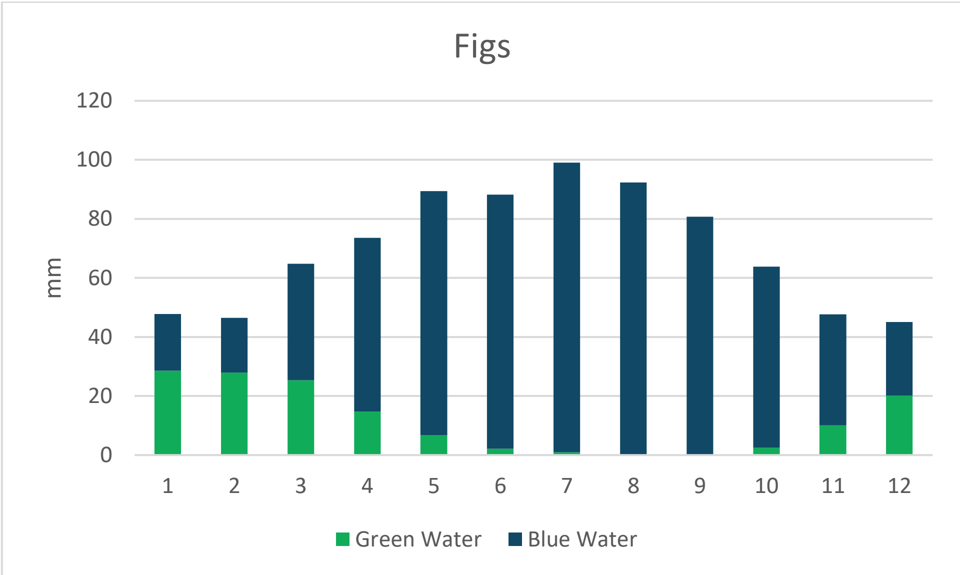

Figure 18 Monthly millimetric green water use and blue water requirement for figs in the Egyptian NEL, for the average year 2016-2021.

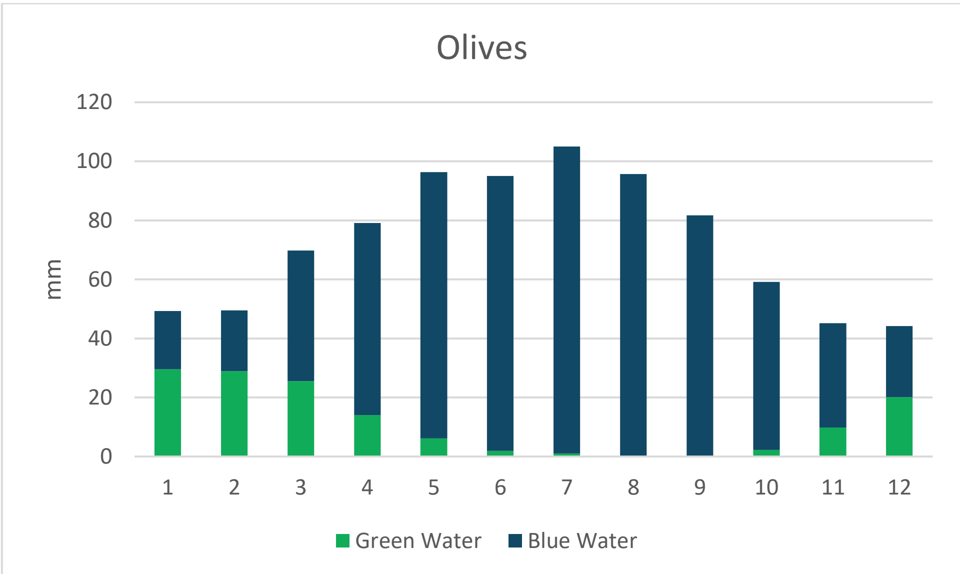

Figure 19 Monthly millimetric green water use and blue water requirement for olives in the Egyptian NEL, for the average year 2016-2021.

3.4 Model expansions to tackle the NEL challenges

In order to face with the strategies identifies during the NEL meeting and accordingly to the NEL grand challenges defined by the NEL leader, few model expansion tools has been incorporated in WATNEEDS; namely a tools for the energy required for irrigation, the agrivoltaics analysis and the salinity tool, whose aim and functioning will be presented below.

3.4.1 Energy for irrigation

Being the WEFE NEXUS focusing on water and energy, the first tools we start to plan is an energy tool for the computation of the energy requirement for irrigation. This tool has been conceived to analyse the situation of the Spain NEL, where energy represent the main aspects to focus on, but it can be use for studying all the NEL and their specific challenges.

The energy tool computes the energy requirement for lifting and distributing the water over the field, considering the field dimension and the water source for surface, sprinkler, and drip irrigation systems.
For each crop type, each field dimension, each irrigation system, and each water source the quantification of the energy needs has been carried out. The analysis is based on the quantification of the volume of water withdrawn and the hydraulics head necessary to lift the withdrawn water and distribute it over the field.
Depending on the irrigation system adopted, the amount of water withdrawn is different due to the different irrigation efficiency of each system, which has been fixed equal to 60 and 95% respectively. Those values can be adapted to each NEL based on the specific information that is collected.
For what concern the hydraulic head, we considered it as the sum of the initial head to transport the water from the source to the field and the distribution head associated with the irrigation system used.
More in detail, the initial head in the case of a surface water source has been fixed to 3m to uptake the water from the source plus the energy losses due to transportation in an open channel from the source to the application point. When groundwater is used, the initial head is considered equal to the depth of the groundwater table, meaning that the water has to be pumped from the groundwater table to the surface. The distribution head for surface irrigation is 0, being the water distributed over the field thanks to gravity. On the contrary, in the case of sprinkler irrigation, a value of 30bar was assumed for operating the pressure plus the losses due to transportation of water into the laterals that have been assumed not to exceed 20% of the operational pressure as in Dacchache et al., 2014.

3.4.2 Agrivoltaics

A smart strategy for producing the needed energy for irrigation, or, more in general, to promote a more efficient, multipurpose, use of the soil is represented by agrivoltaics. Agrivoltaics is becoming a major innovation trend in European countries: the Italian government has allocated 1.5billion € specifically for financing agrivoltaic systems (ref.). In the context of NEXUS NESS, agrivoltaics is a prominent example of positive Nexus interactions, where the Nexus components act in a cooperative, non-competitive way. It has been used as case study during the Innovation Ecosystem Masterclass, and it has emerged as a possible solution during some of the NELs first workshops. Therefore, we decided to develop a model component able to simulate the hydrological effects of the changed evapotranspiration conditions caused by the presence of panels above a cropped surface.

In particular, the agrivoltaic tool modifies the radiation parameter of the potential evapotranspiration to model the shading effect of panels. As a consequence, crop water requirements are reduced. Therefore, the productivity of crops can be impacted in two opposite ways: it can reduce, because the growth processes are slowed down, or it can increase, because, especially in situations of water scarcity, a lower crop water requirement can alleviate the plant’s water stress. This balance is evaluated by the tool in terms of actual (water-stressed) crop yield. The resulting balance determines whether a given crop, in a given location, is suitable for conversion to agrivoltaic system. We normally define 20% of maximum yield loss, i.e. if the crop productivity increases, or decreases by less than 20%, agrivoltaic is a sustainable solution, but this threshold can be co-defined.

More in general, this approach can be re-used for any type of intervention that modifies the parameters influencing the potential evapotranspiration, i.e. that modifies the cropped field’s microclimate.

3.4.3 Salinity

Being saline intrusion a common problem in coastal basins, including the Val di Cornia basin, a tool for quantifying the impact of salty water used for irrigation has been developed. Combined with the water moisture balance in the active layer, we also modelled the salt balance. Depending on the salinity level of water, additional water can be necessary to bring back salinity concentration below a maximum threshold function of the crop type that is harvested. Being a function of the soil moisture at each temporal interval, the adoption of a different irrigation system may vary the level of salinity in the soil, thus ensuring better or worse production conditions. Accordingly, to the outcomes of the NEL meeting, this tool can provide a possible strategy to check and test solutions for reducing the effects of salt in the agricultural production.

4. Model communication and dissemination

The Innovation Ecosystem Methodology NEXUS-NESS uses for the co-development of WEFE Nexus Management Plans requires a meticulous design of the information flow between the nodes of the project network. This has been, for instance, at the core of the NEL workshop training provided to the NEL leaders and to the whole NEXUS-NESS team. Among all the NEXUS-NESS project actions, modeling tasks are the closest to traditional science. Thus, in the context of the project, the problem of transferring information from the modeling WP to other network nodes is particularly delicate. A trade-off arises between transparency and efficacy of the method used for communicating, and the optimum in this trade-off is strongly dependent on the familiarity and expertise of the target with the science behind the models. Therefore, it is crucial that the communication of modeling operations and results is tailored to the audience. In response to this necessity, two different sets of actions have been undertaken to communicate the models to the project partners and to the NEL stakeholders, and the dissemination of the model externally to the project will also have to be tailored to academic and general public.

4.1 Communication to the project partners

The communication of the model to other WPs and project partners has been constantly ongoing since the early stages of the project. The main mean of communication has been oral presentation supported by slides. The presentations have been delivered within different project meetings, online and in presence, and thus they have been designed to fit, from time to time, the context and main aim of each meeting. For instance, a more general introduction to the models has been given during the pre-kick-off and kick-off meetings, while specific technical details have been provided during the first General Assembly, thus favouring in-presence meeting for addressing more complex issues. Moreover, the model presentation provided during the Innovation Ecosystem Masterclass is less technical than other presentations, so that it can serve the double aim of providing an introduction of how models work in the Innovation Ecosystem Methodology and support the training of the NEL leaders for the communication in the NEL workshops. A complete report of the presentations delivered is presented in Table 1. A more technical presentation, targeted to the NEL leaders, is in the planning phase. This presentation will turn to the detailed description of the model provided during the first General Assembly, but with a more NEL specific focus, made possible by the progress made in the NELs during the last months.

Table 1 Presentations delivered by WP4

Date	Meeting	Title	By	Aim/Focus
24.04.2022	Pre-Kickoff	Designing innovative ways to sustainable water resources management developing theoretical and applied approaches bringing them to the real world	SSSA	Introduction to research group and FREEWAT model

24.04.2021	Pre-Kickoff	Polimi-WEFE NEXUS-NESS project	POLIMI	Introduction to research group and WATNEEDS model
29.06.2021	Kickoff	The WATER NEXUS Research Group at Scuola Superiore Sant'Anna	SSSA	
29.06.2021	Kickoff	Politecnico di Milano	POLIMI	Introduction to research group and WATNEEDS model
06-07.09.2021	Master Class	NEXUS-NESS WP4 presentation	POLIMI	WATNEEDS as a Nexus modeling tool. The role of WATNEEDS in the Innovation Ecosystem Methodology
03.02.2022	WP2-WP3-WP4 Meeting	Modelling data and expected results	POLIMI	Role of WP4 in the project. WATNEEDS and FREEWAT for WEFE Nexus modeling. Preliminary results of WATNEEDS (testing phase). Role of modeling in co-designing Nexus solutions. Data request.
30.03.2022	1st General Assembly	WP4-modelling	POLIMI	Role of WP4 in the project. Applications of WATNEEDS and FREEWAT for WEFE Nexus modeling. Preliminary results of WATNEEDS (testing phase). Soil water balance, water scarcity.
09.06.2022	Biweekly Nexus status meeting	From Workshop to Model (and back!)	POLIMI	Updates on WATNEEDS adaptations to the NEL grand challenges General procedure for the WP3-WP4 iterations Applicative example: transforming statements from the Spanish NEL into model specifications
16.06.2022	WP leaders meeting	WP4	POLIMI	Updates on WP4 Tasks, Milestones and Deliverables
04.07.2022	2nd General Assembly	WP4	POLIMI	Updates on WP4 Tasks, Milestones and Deliverables Updates on model adaptations and expansions (WATNEEDS) Preliminary results.

The leitmotif of many of the presentations is the use of simple infographics to describe the functioning of the models, from the biophysical point of view as well as in terms of data pre- and post-processing, but also for the interaction of the models with other project actions. For instance, the infographic reported in Figure 20helped present the distinction between green water and blue water, and their impact on different water scarcity indexes, in an intuitive way, making the knowledge of complex hydrological issues available for project partners with no hydrological background, and for NEL leaders to transmit it to the NEL stakeholders.

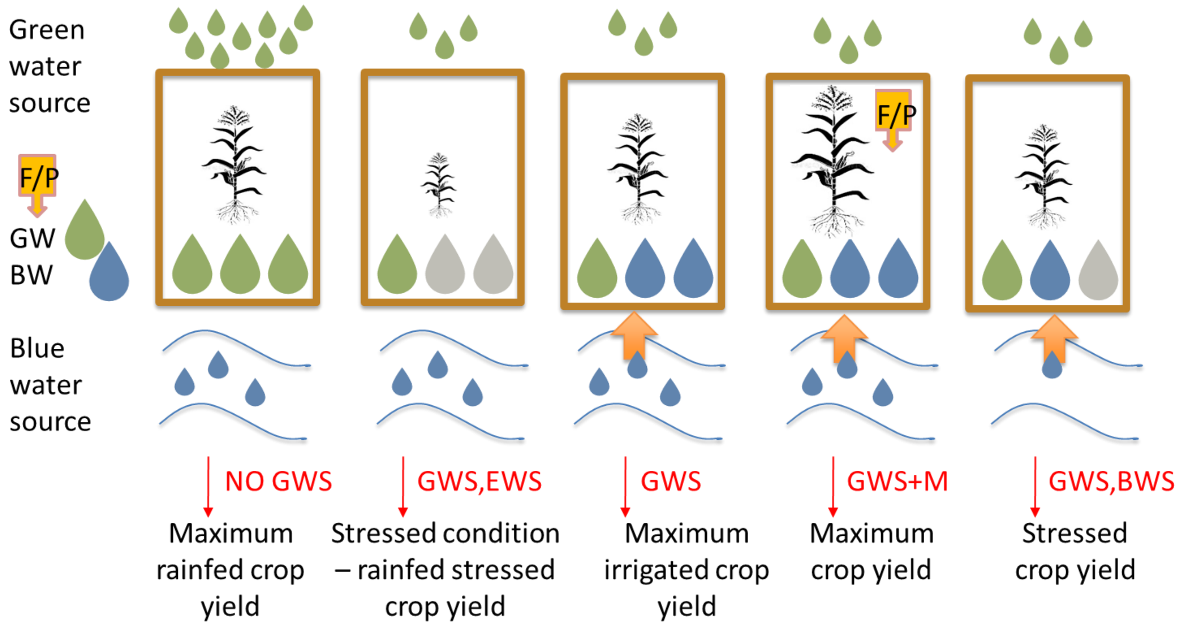

Figure 20 Infographic describing the distinction between green water and blue water, and the different effects on water scarcity indicators.

4.2 Communication to the NEL stakeholders

The first instance of communication of the models to the NEL stakeholders are the model descriptions provided in the NEXUS-NESS website. The flyers designed by WP6 in collaboration with WP2 and WP3 as first mean of contact between NEL leader and NEL stakeholders included the link to the website, so the models have been present in the NEL communications, although indirectly, since the beginning of the project. However, a more tailored communication of the model was needed especially in the light of the trust building process and change motivation process that are necessary to engage stakeholders in an Innovation Ecosystem with a strong modeling core. In this, the role of NEL leaders is crucial, because they are the only technical staff that have both extensive knowledge in Nexus modeling and of the case study, making them the privileged interlocutor between the project and the people the project impacts. Building up a model communication strategy is still an ongoing process. The main reason for this is that providing too many details on the project modeling capabilities may bias the co-definition of the NEL grand challenges, drifting the discussion within the NELs towards challenges that seem better suited to be addressed by the models. Moreover, each NEL has stakeholders with different levels of expertise and different past participatory management experiences, that must be taken into account. For instance, the stakeholders in the Spanish NEL have familiarity and experience with modeling tools similar to WATNEEDS, and so the trust gaining process passes through technical presentations of the results that shed light on the model capabilities and its innovation potential. On the other hand, stakeholders in the Italian NEL have a longstanding experience with using FREEWAT, therefore, showing what the models can bring to the NEL is not as crucial as stating how this project is innovative with respect to the previous experiences. Conversely, in the Tunisian and Egyptian NEL, showing what the model can bring to the NELs, in terms of impacts rather than in terms of results, is exactly what matters, because the familiarity of (part of) the stakeholders with hydrological modeling is lower, and thus the trust gaining process might become more impervious if the communication is made excessively complex. In addition to that, the use of English as a universal language might not be as common outside of the scientific community, making the NEL leaders' role of intermediary even more important. In response to all of these issues, a joint effort by WP2, WP4 and WP6 created a model storytelling product, in the form of a video with an associated screenplay, able to show in a clear way how modeling tools are used for the co-creation of Nexus management plans. WP2 provided knowledge on how to implement storytelling in scientific communication, WP4 produced the video and provided the knowledge necessary to produce truthful content, and WP6 supervised the quality of the final product. The NEL leaders then translated the video screenplay in the local language. All NELs with exclusion of the Spanish NEL showed the video during the first NEL Workshop, mostly at the end of it, so to instil the idea that all the instances emerged and collected during the Workshop, and all the data provided, will be used by the NEL leaders in an innovative, but at the same time ethical and transparent way.

4.3 Dissemination

The work carried out for improving the WATNEEDS model have supported the publication of two articles by Chiarelli et al., (2022) and Galli et al., (2022) based on the quantification of green and blue water under the NEXUS perspective.

Chiarelli, D.D., D'Odorico, P., Müller, M.F. *et al.* Competition for water induced by transnational land acquisitions for agriculture. *Nat Commun* **13**, 505 (2022). https://doi.org/10.1038/s41467-022-28077-2.

Galli, N., Dell'Angelo, J., Epifani, I. *et al*. Socio-hydrological features of armed conflicts in the Lake Chad Basin. *Nat Sustain* (2022). https://doi.org/10.1038/s41893-022-00936-2

An abstract titled 'Using hydrological models to support participated and co-created strategies for water management' has been sent to the *Giornate dell'Idrologia* hold in Genova from 9 to 11 November 2022.

5. Use of the outputs and connection to other WPs

The model outputs presented in this deliverable have two main aims. The first one is to test the model adaptations, and the data delivered by the NEL. This has been done by comparing outputs of the new version of WATNEEDS with outputs, for the same period and region, of the original version. This test has been successful, as, while differences are visible due to the increased quality of the input data and the increased spatial resolution, no differences in the results have been registered such to question the physical accuracy of the models. Further tests are ongoing to verify the completeness of the input data provided, their correct implementation in the model, and the overall coherence among the spatial aggregations of model results and the NEL-level statistics provided by the NELs. The second aim is to provide a baseline for the evaluation of the impacts of different problems and solutions identified during the first NEL workshops. In this case, the interaction between WP4 and other WPs will be crucial. The creation of the model expansions and of some of the model adaptations was also aimed at planning ahead of the NEL workshop outcomes, so to be ready to model the NEL instances when they are presented to WP4 by the NEL leaders. Figure 21 shows the operative steps proposed by WP4 to structure the flow of information from the NELs to the modeling tasks, and back to the NELs in form of results. The modeling team receives information from the NELs through the NEL leader. This information includes the model input data described in the previous sections, but also the voted statements coming from the NEL workshop World Café, the reports of the workshop, and the expert opinion of the NEL leader and their team, which can act as a filter and prevent subjectivity risks for some statements. A discussion is necessary among the NEL leading team and the modeling team, with the support of all those involved in this information exchange pathway, to transform the voted statements into model specifications, and to decide which model is the most suited to address each of the statements. The type of quantifications that can be made regard of course water use, but also land use, agricultural productivity, economic assessments (with the support of WP5), and, thanks to some of the expansions, energy use. The types of scenario simulations that can be run are several, as they can be built "around" the modeling core: feasibility assessments could determine if the resources in the NEL (water, land, sustainable energy) are sufficient to cover the demand resulting from a specific action; optimization procedures could be used to size scalable actions; minimum vs. maximum limit scenarios could be used to determine the space of action that is available for a given strategy, etc.

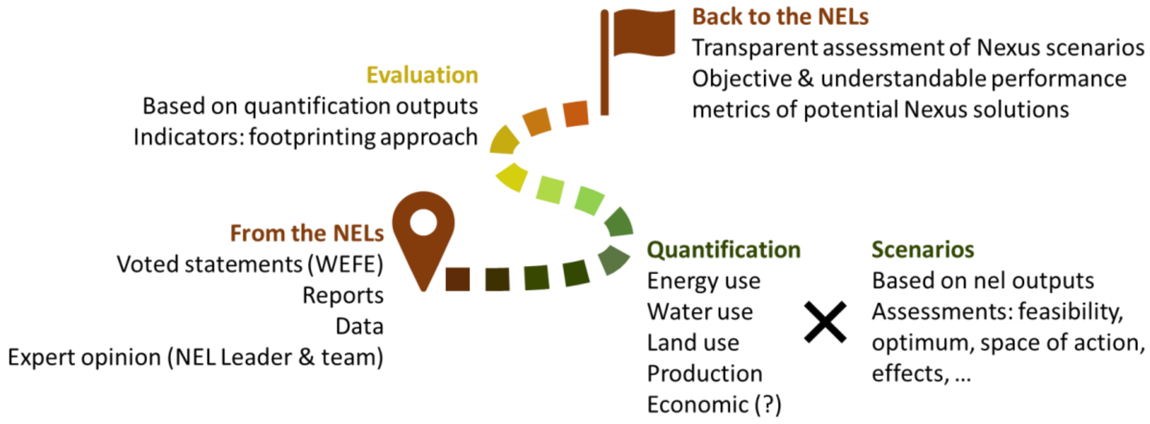

Figure 21 Proposed information exchange pathway to model the NEL transition.

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The results of these analyses will not generally be presented to the NELs in their crude form. They will instead be handed over to the indicator tasks in WP3 and WP5, so that the *quantification* of impacts estimated by the models can be transformed in a more critical *evaluation* of impacts, measured by more Nexus-explicit indicators. The main approach used here will be the footprinting approach, which allows to compare different, even complex, strategies, in a simple, robust and transparent way that relates to the founding elements of the WEFE Nexus. This is the form in which the results will return to the NELs, so that they are provided with a clear assessment of Nexus scenarios, made of objective but understandable performance metrics. In this way, these results can be the basis for further discussion within the NELs, and the starting point for the next phase of the transformation process.

The other, more long-term task of models in the NEXUS NESS project is the creation of an interactive dashboard where the user can obtain evaluations of the impacts and performances of different Nexus strategies.

Transforming WATNEEDS into a multiscalar and ductile tool is an important step made in this direction. In fact, the creation of the dashboard is planned to start from the generalization at the Euro-Mediterranean scale of the key strategies identified in the NELs. Therefore, it is important for the models to be able to model the same phenomenon at different resolutions, so to present results in a multiscalar way. In fact, the optimal resolution for modeling the NELs might produce results at the Euro-Mediterranean scale that are to heavy to ensure a quick responsiveness of the interactive component of the dashboard.

For the same reason, the core of the dashboard will be a set of discretized, superposable scenarios. For instance, different degrees of implementation of the same solution can be visualized, so to see potential nonlinear responses of the system (e.g., does the water use by sunflowers double if I double the harvested area? Will it be less? Or more?). As a further example, simulations of different combinations of solutions can be provided to the dashboard, again to demonstrate possible nonlinear responses, this time in terms of superposition of effects (e.g., does agrivoltaic on carrot fields compensate the additional energy requirements needed to irrigate currently rainfed maize fields?). The choice of discretized scenarios instead of an entirely customizable online modeling tool is sub-optimal only in appearance, because it entails a series of advantages. First of all, WATNEEDS is a research tool with no graphic interface as of today, and a continuous updating and improving process. Therefore, the provision of progressively updated versions in an user friendly format would end up slowing down the improvement process of WATNEEDS. On the other hand, FREEWAT is a set of tools working on open source softwares with its own platform, so duplicating the sources for the tools might generate ambiguities in the case of software updates. Moreover, the simulation times of the models can become high (hours/days), especially on personal, non-professional computers, hindering the accessibility of the dashboard.

Also, despite the adaptations, both models remain, to some extent, data intensive and complex to use beyond their basic form. Thus, having to set externally the model inputs and the simulation modes would increase the possible scenarios, but at the price of reducing dramatically the potential audience of users of the dashboard.

6. Final remarks

This deliverable reports on the adaptation of the WATNEEDS model to tackle the NEL challenges and provides preliminary results for the as-it-is situation in the NELs. These results are defined as "preliminary" even though the model adaptations provided in this Deliverable are successfully tested and fully operational, mainly because locally sourced data require further testing. For instance, results in Italy are not presented in terms of volumetric water consumption because the locally sourced data con cropland extensions, shown in Figure 6, requires an additional validation process that is currently ongoing. The same holds for the extent of barley harvested areas in the Egypt NEL, as mentioned in section 3.3.4. More in general, physical models run with locally sourced data require additional post-run testing done in collaboration with experts having also local knowledge of the target region (in our case the NEL leaders and their teams), to evaluate the consistency of the model outputs as a response to the accuracy of the model inputs. In the same way, these results present a general picture of the hydrological aspects of the NELs' agrifood systems. This picture can and will be adjusted and refined basing on the outcomes of the NEL workshops, both in terms of refined definition of the NEL grand challenges, and, as already mentioned, in terms of instances, proposed interventions and strategies coming from the NEL stakeholders and formalized with the collaboration of the NEL leaders and their teams.

7. References

Allen, R. G., Pereira, L. S., & Raes, D. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56 Table of Contents. In *scscourt.org*.

Chiarelli, D.D., Passera, C., Rosa, L., Davis, K. F., D'Odorico, P., & Rulli, M. C. (2020). The green and blue crop water requirement WATNEEDS model and its global gridded outputs. *Scientific Data*, *7*(1). https://doi.org/10.1038/s41597-020-00612-0

Chiarelli, Davide Danilo, Passera, C., Rosa, L., Davis, K. F., D'Odorico, P., & Rulli, M. C. (2020). The green and blue crop water requirement WATNEEDS model and its global gridded outputs. *Scientific Data*, *7*(1), 1–9. https://doi.org/10.1038/s41597-020-00612-0

FAO. (2014). The Water-Energy-Food Nexus - A new approach in support of food security and sustainable agriculture. *Food and Agriculture Organization of the United Nations*, 1–11.

Foglia, L., Borsi, I., Mehl, S., De Filippis, G., Cannata, M., Vasquez-Suñe, E., Criollo, R., & Rossetto, R. (2018). FREEWAT, a Free and Open Source, GIS-Integrated, Hydrological Modeling Platform. *Groundwater*, *56*(4), 521–523. https://doi.org/10.1111/GWAT.12654

Rossetto, R., De Filippis, G., Borsi, I., Foglia, L., Cannata, M., Criollo, R., & Vázquez-Suñé, E. (2018). Integrating free and open source tools and distributed modelling codes in GIS environment for data-based groundwater management. *Environmental Modelling & Software*, *107*, 210–230. https://doi.org/10.1016/J.ENVSOFT.2018.06.007