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Water Flows Accounting of the Green Infrastructure in the Barcelona Metropolitan Area

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Title Page

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Abstract

This paper proposes an innovative way of accounting for water metabolism in metropolitan territories, and aims to provide a diagnosis of the current situation by measuring and connecting the multiple parts of a complex system, such as a metropolitan area and its green infrastructure, to establish possible constraints and opportunities for future changes in the territory. We provide an innovative framework that generate a series of indicators to characterize the water metabolism of the green infrastructure and the implications for the metropolitan system, in the form of distribution of the water use patterns across multiple scales of analysis and territorialized indicators of water requirements. In particular, we develop the methodological framework using the case of the Barcelona metropolitan area. We believe that the resulting indicators are useful for decision makers of territorial planning and management, as the outputs can quantify how changes in land uses or vegetation cover can lead to changes in the use and availability of water resources.

Keywords

Water Resources; Water System; Vegetation Water Requirement; Social Metabolism; Nexus Assessment; MuSIASEM.

1 Introduction

From a metabolic perspective on material and energy flows, urban systems are open and completely dependent on biophysical inputs from external sources. They are net importers of energy, food and other materials extracted from far areas abundant in natural resources. It is well known that urban systems concentrate processing and consumptive societal functions whereas relying on the extractive ones (Kennedy et al. 2015, Grimm et al 2008, Rickwood et al. 2008). Even in the case that they could produce some of their own clean water, energy carriers or food, space in urban areas is limited and competition hard. Consequently, activities demanding large areas like food production tend to represent a vestigial share inside urban areas.

Metropolis are a case of urban systems with particular, nested dynamics of resource use (van den Brandeler et al. 2019). They are larger territories, merging multiple urban cores and having the potential of integrating a mix of land uses aside from urban areas. Hence, they represent a progressive connection between the rural areas and the urban and peri-urban ones (DTS 2017), potentially providing a relevant share of the ecosystem services that they require through surrounding areas, namely the green infrastructure (Benedict and McMahon 2002). This infrastructure is comprised by farming areas, natural habitats (although heavily anthropized) and parks, and these areas host agricultural, forestry and leisure activities with key roles at providing ecosystem services (Tzoulas et al. 2007, Hansen and Pauleit 2014, Depietri 2015). The supply and quality of ecosystem services of provision, regulation, support and culture are as important as of the mobility, energy or telecommunication infrastructures, since they set the quality of the environment in which population lives. Considering the green infrastructure as a crucial element of metropolitan areas entails some requirements for its reproduction and maintenance (Marull et al. 2020). Changes in the composition of green infrastructure through territorial planning can lead to alterations of ecosystems functions and variations on the supply of services and goods towards the metropolitan system, heavily affecting populations' living standards. At the same time, the green infrastructure affects the metropolitan dependency on external inputs and its sustainabilty and circularity, since it has the capacity to internalize some impacts into the metropolitan territory using its own natural resources.

Water is one of the key elements for those reproductive processes and yet the most forgotten in metabolism studies (Eurostat 2013). Part of this lack is due to data availability issues (Naff 1999) which difficult the construction of robust and comprehensive databases on water flows in cities, in general, and across green infrastructure, in particular. In this work, we use an integration of tools from social metabolism and landscape ecology to propose a framework for the accounting of urban water metabolism for green infrastructure. The document will focus on giving a response to two particular questions: i) how to assess water requirements in metropolitan area's green infrastructure and ii) what are some of the potential implications of modifying the extension and composition of the green infrastructure sectors (i.e. parks, forests and agricultural areas). In particular, the contribution of this study consists in providing a more comprehensive perspective of the performance of socio-ecological systems through the water metabolism approach offering land planners and policy makers a planning tool capable of generating a series of useful indicators.

We use an application of the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Giampietro and Mayumi 2000, 2001, Giampietro et al. 2009) for the application of water metabolism (Madrid et al. 2013) to structure water flows; and landscape ecology to deal with the intricate arrangement of land uses and activities performed in large and complex territories such as metropolis (Marull et al. 2019). After this introduction, we will briefly highlight how we adapted MuSIASEM to approach water metabolism in section 2, present our accounting methodology in section 3 and our results in section 4.

2 Conceptual approach

2.1 MuSIASEM: a fund and flow approach for water studies

Similar to organisms, societies metabolize materials and energy to perform activities of their economies for self-reproduction in the form of flows that can be measured in physical units. The societal metabolism approach assess in comprehensive ways the performance of territories, focusing on analysing directly the biophysical structure of the system and the exchanges of the economy (Lotka 1922). The development of this concept resulted in different approaches of biophysical accounting (Gerber and Scheidel, 2018). Of those, the MuSIASEM approach is particularly useful for the multi-scalar and multi-dimensional analysis and it has been applied to several case studies (e.g. Ramos et al. 2007, Sorman et al. 2009, Giampietro et al. 2011, 2014, Arizpe et al. 2012, Siciliano 2012, Scheidel et al. 2013).

One of the interests from a reproductive perspective useful for sustainability goals is that MuSIASEM quantifies flow elements in relation with fund elements. In this sense, flow elements (like water, energy or food), quantify what the system is doing, whereas fund elements (like population or land) are characterizing what the system is made of, representing what must be reproduced to maintain the system, as well as giving a metric of its size. Thus, flows are put in relation with the extension of the system where they are occurring, providing a ratio of flow/fund relation that represent the metabolic pattern. For instance, we account the water requirement in terms of litres per square meter, assessing not just the absolute numbers of flows but the relative metabolic performance of each part of the system. The consideration of these flows and fund elements to characterize socioeconomic systems is based in the bio-economic approach proposed by Nicolas Georgescu-Roegen (Mayumi 2002).The MuSIASEM approach can provide indicators to distinguish among feasible, viable and desirable constraints. Feasibility refers to constraints imposed by nature out of human control, like climate, terrain topography, or the water from precipitation. Viability refers to the constraints under human control depending on the technology, economy, demography or institutional aspects. Finally, the desirability would depend on the preferences of the population, determined by their values and culture, as for example one solution could be feasible and viable (e.g. all population drinks recycled water only), but nobody is willing to choose that as an option (Saltelli and Giampietro 2017). While in this document we propose a biophysical and socioeconomic representation of the feasible and viable constraints of the water, the desirability should be checked extending this assessment with participative methods or indicators about the population’s preferences.

2.2 Water metabolism and landscape ecology

In a metropolitan area, water is necessary for many social and economic functions, but it also has important ecological functions necessary for the reproduction of the conditions of the biota of ecosystems. Water is basic for the biological reproduction of the living parts of the system, including the flora and fauna of the ecosystems, the primary production of crops and animals, as well as humans. On the other hand, water extraction, distribution and consumption require important economic investments in appropriate infrastructures for capturing, treating and distributing it to the different uses.

In MuSIASEM, the water accounting is done classifying a set of semantic categories of water uses across the water cycle. Previous studies using the MuSIASEM approach have mostly been applied to assessment of agricultural systems either for accounting and characterization of water flows (Serrano-Tovar et al., 2014), or for assessments of the water metabolism and its environmental impacts (Cabello-Villarejo & Madrid-López, 2014; Madrid-López et al., 2014; Salmoral et al., 2018). These studies focused on the role that water has to maintain an economic sector (agriculture) and a societal function (food production). However, to the best of our knowledge, this approach has never been applied to the specificities of metropolitan systems, where urban systems are mixed with rural and natural areas in the same territory. An approach like this would be useful for territorial planning and management of water in metropolitan areas.

Different patterns of societal metabolism configure certain landscapes providing ecosystem services for the metropolitan areas. Therefore, Landscape Ecology methods are useful to identify land use patterns and their associated ecological processes (Dupras et al. 2016; Marull et al. 2018a). The combination of societal metabolism with Landscape Ecology results in a series of indicators that can be territorialized, and thus be represented spatially in maps using GIS tools (Marull et al. 2016; Marull et al. 2018b). One of the contributions of this combination is the assessment of multi-dimensional approaches (eg. water and land uses) to open spaces of metropolitan systems, which increase the comprehension and capabilities of the territorial planning and management of green infrastructures.

3 Methodology

3.1 Study area

The Barcelona Metropolitan Area (BMA) consists of 36 municipalities with more than 3.3 million inhabitants, and it extends through 636 Km^2 (Figure 1). The cities and towns around Barcelona conforming this metropolitan system represents almost half of the Catalan population and it represents a strategic economic zone since it connects Spain with the rest of Europe and the Mediterranean Sea. Around half of the surface is urbanized, but the rest is composed of a mix of agrarian areas like the Llobregat Delta and four mountainous areas hosting diverse natural habitats and rural uses: the *Serra de Collserola*, *Massís del Garraf*, *Muntanyes de l'Ordal* and *Serralada de Marina*. Mean annual precipitation averages 642 mm and ranges 376-862 mm with a clear pattern of maximum precipitation during autumn and spring and dry summers (Ninyerola et al. 2000). The climate is coastal Mediterranean, with high water stress during summers.

This work firstly distinguishes the metropolitan system into urbanized areas and the green infrastructure. Urbanized areas consist of housing, commercial and industrial sectors and they concentrate high consumptive and productive economic activities. Green infrastructure consists of three sectors: forestry (which includes all the natural habitats such as forests, scrublands, meadows and wetlands), farming (including crops and livestock) and parks (including urban and peri-urban parks). Further subdivisions could be done according to the specific focus of the study, for example if it is necessary to differentiate between types of crops or other habitats, as it will be shown below. Data for figures of the overall distribution of water for the BMA are taken from the available statistics and the published reports by Àrea Metropolitana de Barcelona (AMB 2019, Servei de Redacció del Pla Director 2017, 2019).

3.2 Estimation of green infrastructure water requirements

The green infrastructure is mainly characterized by areas covered by vegetation, either wild plants in natural habitats, grass and ornamental plants in parks, or crops grown for humans or for feeding livestock. Given that the real amount of total water used by vegetation of a metropolitan system cannot be directly measured because it would imply countless primary inputs from *every* plant within the territory, what this study proposes for studying large scale territories is to use water consumption estimations based on models used by agronomists, which provide the best indicator available to represent the water that different parts of the green infrastructure require. For the illustrative aims of this study it has been used the Hargreaves method for estimating the different evapotranspiration of the vegetation in the system (Hargreaves and Samani 1982). This method is established on basic climate data to estimate a Potential Evapotranspiration (ET_o), and then it includes the evapotranspiration coefficients for each plant (K_c) to obtain a final estimation of the total evapotranspired water (ET_c) in a specific place and time (Eq. 1).

Eq. 1

$$ET_c = ET_0 \times K_c$$

The Hargreaves method estimates ET_o based on maximum and minimum air temperature, and is written in Eq. 2 as

Eq. 2

$$ET_0 = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a$$

where T_{max} = maximum air temperature (˚C), T_{min} = minimum air temperature (˚C), R_a = extraterrestrial radiation ($MJ \cdot m^{-2}$). Extra-terrestrial radiation, R_a, is estimated based on the location's latitude and the day of the year. Therefore, the estimation on water requirements for preserving the main source of biomass (the Net Primary Production) is based on two factors: the characteristics of the vegetation cover and the climate determined by the spatial location.

Data for temperatures at month level are taken from Atles Climàtic Digital de Catalunya (Ninyerola et al. 2000), which results in a map showing the differences of ET_o in the BMA. Crop coefficients (K_c) are obtained from the Food and Agriculture Organization of the United Nations (FAO) (Allen et al. 1998). The water requirement estimated in this study is shown for an annual basis, so a leverage procedure must be done for crops based on their growing times along the year, which it is also available from Allen et al. (1998). Soil evaporation when crops are not being grown is expressed also as an equivalent coefficient to K_c in the calculations, in this case is assumed as 0.15, which is a value recommended by FAO for simplification when primary data is not available to adjust the value for each specific soil.

Data on the type and amount of surface for each crop is taken from the land cover map MCSC-2015 (CREAF 2015), and food production statistics from the Departament d'Agricultura, Ramaderia, Pesca i Alimentació of the Generalitat de Catalunya (DARPA) (Marull et al. 2019a).

The methodology for estimating water requirements has been originally created for irrigation needs of crops, but this study propose to use a similar approximation to estimate the water requirements for the preservation ecological functions of the green areas which are not part of farm exploitations, by calculating the evapotranspiration of the dominant plant species that populate these habitats. Usually data sources like FAO do not list wild plants not used in agriculture, but it is possible to set an approximation based on the species coefficients (K_s) of the mix of main plants found in these natural ecosystems. The mix of dominant plant species of each habitat of BMA is obtained from *Manual dels hàbitats de Catalunya* (Carreras et al. 2016) and the K_s for non-crop species was found in the extensive *Manual de Riego de Jardines* made by Junta de Andalucía (Avila 2004). The natural habitats of BMA are also determined using the same land cover map MCSC-2015 previously mentioned.

3.3 Indicators of water performance

The aim of the study is to provide with a series of indicators of water performance about i) the general performance of the water metabolism at the overall scale of the whole metropolitan system, and ii) the implications of the green infrastructure to the water performance of the metropolitan system. The results of the water accounting at the upper scale of the metropolitan system reflect indicators about: water volumes for each relevant system component, feasibility and viability of the water system, level of openness, dependency and self-sufficiency for the metropolitan water resources, potential losses, sequential pathway of processes, and water balances. More specific benchmark values about the water metabolism of the green infrastructure include: internal precipitation, internal Natural Supply, green water appropriation, internal blue water appropriation, external blue water imports and local blue water generation.

3.4 Mapping vegetation water requirement

The final indicator is calculated and territorialized into a highly detailed map through GIS tools. After combining the resulting map for ET_o with the K_c of crops and K_s of wild plants, we obtain the ET_c values for each type of plant or mix of plants selected. Then, since the information about what kind of vegetation are present come from the land cover map of 2015 (CREAF, 2016), the average values of ET_o for each land cover polygon in this map is calculated, generating the corresponding spatial association between ET_o and K_e used to make the resulting estimation of ET_c. For the illustrative purposes of this map, apart from the part of the green infrastructure areas covered by vegetation, it was also estimated the evaporation of surface water bodies such as rivers or wetlands, as they also belong to the green infrastructure and they represent a certain part of water loss through evaporation process. Data of their evaporation coefficient was obtained from FAO (Allen et al. 1998).

4 Water accounting of green infrastructure of BMA

4.1 Total water flows in the metropolitan area

In Figure 2, shows the linear classification of the main stages of the water flow for the BMA, from the sources to the end users, based on Cabello et al 2015. This first general scheme distinguishes the water flow stages into parts that are carried out either by humans or take place in nature. Although all of them belong to the same water system, each column represents a domain which require a different analytical criteria and management type, from ecology to infrastructure or economic assessment. This figure classifies what are i) all possible sources of water for the BMA, ii) what are the activities required to supply water, and iii) which are the end uses of these flows. It also categorises water from their primary source, such as surface or ground water, and it later distinguishes the flow between blue water (i.e. directly appropriated by humans), green water (i.e. water as soil moisture that can only be directly used by plants), and grey water (i.e. waste water).

Figure 3 goes more specific and it serves to indicate the origin of water for the BMA from external or internal supply. There are some processes like purification of freshwater that take place both inside and outside the BMA, and there are processes like desalination or treatment of waste water which are happening only inside this metropolitan system. The BMA imports a large share of water from external river systems such as Llobregat or Ter, and the water consumption affects those external systems with a huge territorial imprint (Tello and Ostos 2011). The water consumed in the BMA has a high degree of dependence on the performance of these rivers systems to supply its actual water consumtion. However, the BMA has some ecological funds such as aquifers, soil or natural habitats that act like internal water source, so they must be preserved in order to keep this level of water supply. These water funds belong in effect to the green infrastructure, so their preservation depends on a proper recognition and management. Water interacts with the metropolitan territory through ecological processes of runoff, percolation, evapotranspiration, and soil capture, which in turn represent key routes of vulnerability where humans could create impacts affecting the overall water system. Finally, there are also feedback processes from the water dumped after their use by the socioeconomic sectors (end users), which are either disposed to the ecosystems creating some impacts that can be quantified (like industrial waste waters), are processed by treatment plants for reutilization, or are discharged to the sea.

Figure 4 shows the distribution and quantification of water use in the BMA. While most of the freshwater supply for urban use is provided by two main external water systems (Llobregat and Ter rivers, with approximately 60%), there are still important water flows obtained from inside the territory, coming specifically from internal aquifers, precipitation, sea desalination, few small internal streams, and even from reclaimed water (reutilization). Although this mix of sources supposes a greater degree of complexity in the water management supply system, the same diversification has the potential to contribute on opportunities for alternative uses and resilience.

Regarding the blue water scope, the residential sector consumes the largest share (52%) compared to productive sectors like the agricultural (14%) or the commercial and industrial (29%). This is a different pattern than the one observed at the Catalan region average level where domestic consumption is around 19% and agricultural rises 70% (ACA, 2008). However, when considering also the green water used by the vegetation, the picture changes and the green infrastructure becomes the largest consumer of water in the BMA (41%), due to the large extension of these land uses (forest, scrublands, pastures and other non-agricultural uses) and their related water requirements. Farms and urban parks consume both green and blue water as some of them are also irrigated, but they do not cover an area as big as the forestry, so in absolute terms they do not represent as much water use as the other sectors.

This resulting picture of the water throughput of the BMA represents the base level for the metabolic analysis for this system. When including the most relevant parts of the water system that imply a considerable share of the water use, this comprehensive representation of the water flow in quantitative terms allows to check for balances in the territory. Accordingly, as we will develop in the following points, one can obtain key indicators for assessing the performance of the water metabolism of the territory.

4.2 Water flows in the green infrastructure

The second level of analysis of this work focuses on exploring the water uses inside the green infrastructure. The bottom of Figure 4 shows the water flow distribution among the three selected sectors of green infrastructure in the BMA: forestry (134 Hm^3), farming (54 Hm^3) and parks (33 Hm^3). The total water consumption by these sectors is the result of adding blue and green water used. While farms and parks use some irrigation (blue water), the rest does not use blue water at all, implying that while these areas have a certain demand of water, they depend on natural precipitation and they do not use water inputs from humans. However, their large consumption of green water does have important implications for the overall water balance of the metropolitan area, since it greatly affects the remaining available water. An analysis of these dynamics is relevant for understanding the role of the green infrastructure in the metabolism of water in a metropolitan area, thus providing useful information for territorial planning and management.

This can be further analysed in Figure 5, a diagram representing the role of green infrastructure on the supply and appropriation of water at the BMA. The total precipitation of a certain system can be considered the only water input provided from inside a territory. The Natural Supply of water is the volume of water input that remains in the system after the evapotranspiration process of vegetation. This is the maximum theoretical water quantity that humans could access if they would have the necessary infrastructure, and that is why is relevant to characterize how is the evapotranspiration of the green infrastructure of the metropolitan area. Then, this internal water supply either percolates through the ground, runoff on the surface, or remains as humidity in the soil. In the case of BMA, from the Natural Supply the part that percolates to recharge aquifers is largely used through the exploitation of groundwater for agriculture irrigation in the Llobregat Delta area, but almost all runoff from internal precipitation is not appropriated and it is canalized through channels, pipes and rivers and discharged to the sea. The total human blue water appropriation in the BMA is a combination of this internal Natural Supply (representing 26% of the total blue water used), the freshwater imports from external river systems (70%), and some desalination that occurs inside the BMA (4%). Then, part of this total blue water appropriated by humans is used to irrigate some crops and parks, so the total evapotranspiration of the green infrastructure is at the end the sum of water from internal precipitation and some blue water from humans. It is interesting to note that in the BMA there are efforts to recycle some grey water from urban uses, treat it, and use it for irrigation (becoming 11.8% of the total blue water use for crops).

4.3 Measuring the water performance

Once obtained the previous comprehensive representations of the water metabolism at the BMA level and then at the green infrastructure level, this work establishes a series of performance indicators of water metabolism to support decision makers of metropolitan areas. The feasibility check – the compatibility with constrains imposed by nature and out of human control – and the viability check – constraints depending on human capacities – about water can be now measured and used as benchmark values to compare the current situation with historical values or with changes made by potential scenarios. Those indicators are based on flow balances representing what is the role of both the green infrastructure in the appropriation of water, and its relation with the rest of the water system.

Going back to Figure 4, this diagram offers relevant data for analysts and policy makers about the general performance of the water metabolism at the upper scale of the BMA:

- Different water volumes and relative size of each system component: When contrasted to each other, numbers about water volumes of each element in the diagram indicate which are the most important compartments and what role they play. For example, in Figure 4 becomes clear that the principal contributors to the blue water inputs in the case of BMA are superficial water instead of groundwater (with 77% and 17% respectively), and this water comes mainly imported from external river systems (63% of the superficial water used). Other sources of water like desalination, regenerated and bottled mineral water are also present but they represent a minor contribution to the total amount (8% when added together).
- Some feasibility and viability indicators about the system performance can be determined by ecological and socioeconomic constraints represented in this diagram: The interface of the human needs of water resources with what nature can provide is represented by the compartments of the first stage of Figure 4 about funds and stocks. The water flows are directly or indirectly appropriated by humans from the water bodies available in nature, represented in this diagram as soil humidity, aquifers, rivers and sea. According to the distinction proposed by Georgescu Roegen (1971), a resource for a certain flow appropriated by humans can be considered as a fund element if the system providing can be reproduced at a pace to maintain its functions. The resource would become a stock element when there is no need or possibility to reproduce the system providing the flow, and then the rate of

extraction can be as high as desired. The check on the viable constrains imposed by human capacities can be done when comparing the requirements of water by the end users, at the right side of Figure 4, with the water processing and distribution activities in the middle stages of the diagram. The characteristics of the infrastructure, technology, funding and organization developed by the society are determining the levels of achievement of the provision of water required by the end users.

- The level of openness, dependency and self-sufficiency for the water resources: From Figure 4 it is also possible to determine that the BMA is a very dependent system on external providers, importing almost half of blue water used (47%). Apart from the water withdrawal from some internal rivers (29.6% of blue water), the self-sufficiency for blue water relies on the extraction of groundwater from the internal aquifers (17.5%) which is limited to their slow recharge rate in this area, and to some desalination (3%) and recycled water (1.6%). The low proportion of regenerated water compared to the total amount of waste water is an indicator demonstrating that the BMA (as most of similar territories) is a very open system that imports and also dumps (to the sea) most of the blue water flows.
- This diagram also allows evaluating potential losses in the water system, in this case represented as the share of blue water lost in the distribution networks. An indicator of efficiency of the distribution system can be obtained making the ratio between the amount of water arriving to the end users and the total water flow before losses. For the BMA case, the water distribution efficiency is 88%.
- This diagram also represents a network of relations, establishing a sequential pathway of processes and the dependency among the elements. In this sense, Figure 4 also provides information about possible compensations and trade-offs among system´s compartments, since it is established the quantities of resources available in the different stages of the water flow. For example, in the BMA, it is clear that if in one year cannot be pumped enough water from the internal aquifers, it will be used more water from the rivers coming from outside in order to keep up with the level of agricultural production.

- Finally, this visualization of the system illustrates all inputs and outputs of the water flows, so it is possible to check for balances of the considered flows. As this diagram must show the whole functioning of all elements in the water system, it becomes clear the distribution of water flows and what is missing or left. Therefore, since all parts of the scheme must match quantitatively, it is also possible to double check data about water volumes when compared to their corresponding relations across the sequential stages to find inconsistencies between sources of information as flows must correspond one to another.

On the other hand, Figure 5 presents some resulting benchmark values regarding the implications of the green infrastructure to the current situation of water performance of the metropolitan system. We selected the following set of general performance indicators differentiating between feasible (in green) and viable (in blue) constraints:

- Internal precipitation: representing the input of water in the territory only through precipitation, to establish what the available input of water to the ecosystems without water imports from external systems.
- Internal Natural Supply: is the maximum theoretical available water remaining in the system after the evapotranspiration process. Humans can only use water from this remaining part, depending its appropriation on the water extraction infrastructures available. It corresponds to the supply side of the water provisioning ecosystem service by the green infrastructure.
- Green water appropriation: this is the water in the soil moisture consumed by vegetation, which cannot be used directly by humans, and that exits the system through the evapotranspiration process. It is the result of the calculation of the vegetation water requirement. It corresponds to the demand side of water by the ecosystems of the green infrastructure.
- Internal blue water appropriation: shows the share of water used by humans that comes from internal sources of the system. That is, the water humans effectively extract from the internal natural supply. It corresponds to the direct demand of water by society.

- External blue water imports: represents the imports of water from sources outside the territory considered, that humans use together with the internal sources. This indicator provides information about the water dependency of the territory.
- Local blue water generation: this indicator shows alternative water sources which do not come from either the internal natural supply or the external imports. Desalination and reclaimed water are two of these alternative sources, and they represent an additional input for the water self-sufficiency of the system. They are interesting inputs of water from the management and planning standpoint because they represent opportunities as alternative water sources but with very different socioecological costs.

As this approach is multiscalar, it can also generate indicators of water performance for lower levels of analysis, thus providing information about how water is used by the green infrastructure specifically for certain parts of the territory. At the top of Figure 6 we can see for each one of the 36 municipalities of the BMA the different distribution of the percentages of vegetation water requirements by the natural habitats and crops, and the remaining natural supply of water that could be potentially used for other purposes. In contrast, the bottom of Figure 6 we represents the actual volumes of water used by the forestry and farming sector in cubic hectometres. The comparison shows how different are water performances of the green infrastructure depending on the municipality of the BMA are we focusing on, thus proving a useful analytical tool capable of bridging quantitatively different levels of analysis. While vegetation water requirements show the patterns of the proportional appropriation of water resources by vegetation and the remaining availability for society, the actual volumes of water used provide information about how much water consumes the vegetation of each municipality in the BMA. For example, for the municipality of Sant Climent de Llobregat, Figure 6 shows that vegetation has a huge appropriation of water inside its territory, but then this fact does not mean a big share of the water consumed by the green infrastructure for the total BMA. On the contrary, looking at Sant Cugat del Vallès does not reflect an extreme pattern of water consumption, until it appears to be one of the largest water demanders of BMA due to its large forest surface.

4.4 Mapping the indicator of vegetation water requirement

The georeference of some of the indicators allows to set a very important link between the previous analysis based on a societal metabolism approach and the spatial dimension, as discussed in Serrano-Tovar (2014) and Marull et al. (2019b). In Figure 7 we present the resulting map of vegetation water requirements in the green infrastructure for the BMA territory.

This map shows in detail the quantitative differences in water use that the diverse natural areas and crops represent depending on their specific location. We can see that in general, agricultural areas require more water per unit of surface than the natural ecosystems of the BMA. This can be seen in crop areas with higher water requirements, like in the plain areas of the Llobregat Delta, where surface water and groundwater sources are accessible. Natural vegetation in BMA is generally adapted to the water scarcity imposed by the Mediterranean climate, so forests, scrubs and meadows are mainly composed of sclerophile species or there are deciduous plants that opportunistically appear during rainy seasons (especially autumn). In the map we can also see the differences on locations with riverside forests and wetland vegetation which use more water, and also how urban parks have in general higher demands of water than the rest of the green infrastructure, as they are in many cases covered by grass and ornamental plants that require some watering, especially in dry seasons. For this reason, the BMA administration is implementing a more water efficient park management (for example, using native species that require less watering).

On the other hand, the crops found in the BMA differ on their water requirements along the year. In this sense, general permanent crops like fruit trees tend to use more water at the end of the year, considering that the annual crops can require more water when they are growing, but part of the year the land is not occupied by these seasonal crops. The vegetable orchards and some cereals and forage crops that have more than one harvest per year represent also higher demands of water.

With detailed georeferenced indicators as the vegetation water requirement shown in Figure 7, one can accurately represent how changes made by territorial planning and management could influence the water performance of the system, and where these changes are located. In general, after the outcomes obtained for the BMA, it is possible to anticipate and quantify that, for instance in the case of land shifting from natural areas to agricultural areas would entail more or less water requirements depending on the mix of crops used. This becomes relevant especially when regional planning agencies are considering these land cover changes as potential planning scenarios, as studies in the BMA have suggested that biodiversity could be enhanced by recovering some lands for agriculture, rather than extending forests (Padró et al. 2019). This kind of outputs is especially useful to assess some promising scenarios that increase the level of reclaimed water or use agroecological practices in the territory, which could potentially be translated into a better water efficiency of the agrarian sector in the BMA. In any case, this study shows that it is possible to assess and quantify these future changes in the metabolism of water in metropolitan areas with a combination of methods capable of generating a comprehensive and yet detailed representation of the land changes.

4.5 Limitations and further research

4.5.1 More specific analysis of water throughput

The present study provides a flexible framework about water metabolism showing some preliminary outcomes that can be further developed depending on the particular purposes of the decision makers and actors demanding specific information about water performance in the BMA. For example, a more precise information could be calculated for the estimation of the vegetation water requirement of the green infrastructure by using models such as Penman-Montieth (1998) to estimate the ET_0 incorporating more climatic variables. The actual agricultural practices used in each farm exploitation also create differences in the water requirements, but it necessarily requires fieldwork data apart from the available statistical sources. The water directly used by livestock farming in the BMA is not considered, as it is usually much lower than the water requirements of crops in absolute terms, but anyway it is considered the water consumed indirectly by the livestock feeding on the forage crops of BMA. Urban parks can vary greatly in their water requirements depending on the mix of species used, so knowing the specific mix and amount of vegetation for each park will generate a more accurate result. The estimation of the water natural supply remaining after the precipitation and evapotranspiration could be improved by estimating the factor of leaf interception of the BMA forests, which causes that when rain is lower than a certain threshold, the water from precipitation evaporates before arriving to the ground, decreasing the final quantity of annual water input available from precipitation in some forests.

Other possible variables describing the role of the green infrastructure can be incorporated depending on the specific purpose of the analysis. For example, different soils affect the levels of groundwater infiltration and runoff, thus affecting the ecosystem services that the green infrastructure generates towards the metropolitan system. Fortunately, a detailed cartography of water runoff in the BMA is already provided by a previous study considering soil types made by the Center of Research of Ecological and Forestry Applications (CREAF) and Barcelona Regional (BR) for the Direcció de Serveis Ambientals de l'AMB (Basnou et al. 2014).

The results shown from this framework are based on a yearly average. However, it could be possible to estimate seasonal differences of vegetation water requirements, which will provide more insights about the behaviour of the water system along the year, since important differences arise when temporary crops are grown, and different climatic patterns occur across the weather seasons.

Apart from the estimation of water requirements by the green infrastructure, the picture of the overall water performance of the BMA could be more precise by obtaining more detailed data from the multiple organizations in charge of gathering and compiling data about different stages of the water cycle. For the moment, information about water flows is very fragmented and there is not a single source compiling all the aspects that build up an overall picture like the one generated in this study. While this task is being carried out, this study focuses on presenting the general analytical framework and some useful indicators to characterize water metabolism of green infrastructure at different scales.

4.5.2 Extending the analysis: nexus assessment of a metropolitan area

This study about the water metabolism is designed to also serve as the basis for a full nexus assessment of the societal metabolism of the BMA where other dimensions than water – like energy or nutrients – can be also incorporated into an integrated analytical platform. The nexus assessment between water, energy and food (commonly known as WEF Nexus) makes quantitative connections and thus provide the opportunity for tracking the trade-offs among dimensions that are typically studied and managed separately. This approach represents an innovation for territorial planning and management (Ripa and Giampietro 2017). Figure S1 illustrates how the analysis of the energy and nutrients flows can be represented into the same analytical framework than the one used for the water metabolism shown along this study.

Figure S1 shows that there are the same stages in the metabolic process, although each dimension has different compartments corresponding to its specificities required for the analysis. These compartments can be adaptable to open up the system into the components that are relevant for determining the keys of the metabolic pattern of a metropolitan system. However, the combination of flow elements (like energy, nutrients, food or money) with fund elements (like land uses and human activities), provide quantitative links able to establish the relations among these different dimensions. This type of results can also expand the indicators about water use, for example providing the intensity of water use in the different productive sectors, or the relation of water consumption with soil nutrients or product production. Examples of the powerful outcomes of this nexus assessment approach are illustrated in Giampietro et al. (2014) and in Serrano-Tovar et al. (2019).

5 Conclusions

This paper analyses the water flows of the green infrastructure of the Barcelona metropolitan area through a societal metabolism perspective. This methodological approach represents the performance of water flows through a system (the metropolitan area) and accounts for the water required for different uses of the system.

As discussed, we saw that differently than only focusing on urban systems, metropolitan areas are more complex socioecological systems due to the coexistence with green infrastructure. There is a simultaneity of external dependency with a certain capacity for the self-provisioning of natural resources and ecosystem services. For territorial planning and management, it might be strategic to consider and analyse these internal resources with appropriate tools that can serve to enhance the capabilities and autonomy of these systems, especially considering sustainable and climate change scenarios. For example, metropolis might be able to produce in their territory part of the food or the energy that they consume, but these changes have implications to different dimensions, like the water use. Therefore, studying these complex systems from the societal metabolism approach can provide useful indicators to set some criteria to achieve desired goals in ecological sustainability, self-sufficiency, sovereignty, equity, economic competitiveness and social welfare.

This study used a combination of methods based on the societal metabolism approach with methodologies from landscape ecology like the agronomic estimation of evapotranspiration, or the spatial analysis of the territory and visualization of final outputs. The result is a picture of the performance of water flows that obtained detailed indicators of performance like the vegetation water requirement. This framework allows to provide information for various levels of analysis, including the overall metropolitan area in relation to the green infrastructure, the focus on the sectors corresponding to the green infrastructure (forestry, farming and parks), the distinction of different water patterns corresponding to each municipality of the metropolitan area, or the more accurate spatial representation of the water requirement matching to each land cover in the territory. With this method it can be estimated how changes in land uses or vegetation cover can lead to changes in the use and availability of water resources. We believe that this innovative approach can serve as a useful contribution to decision makers for territorial planning and management tasks of the green infrastructure.

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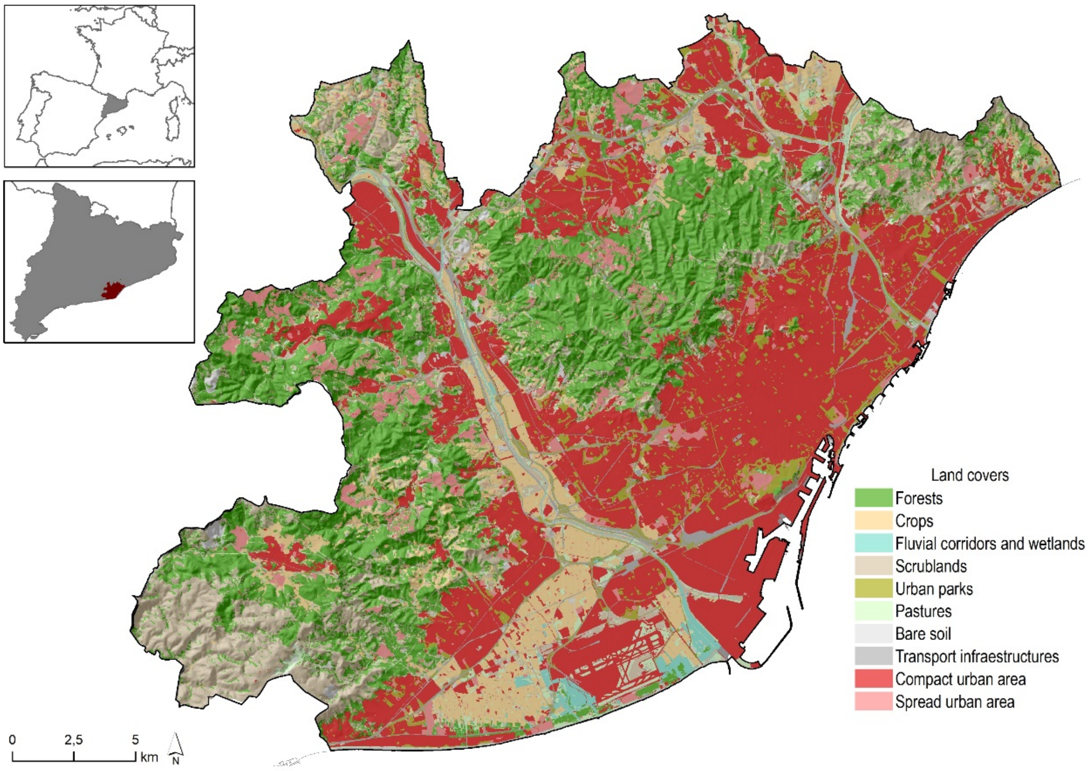
Figures

Figure 1. Land cover map (2015) of the Barcelona Metropolitan Area (BMA).



Source: CREAF, 2015.

Figure 2. Diagram of the main stages of the water flows for the Barcelona Metropolitan Area (BMA). Blue elements correspond to freshwater flows, navy blue elements come from the sea water, brown elements come from groundwater, green elements come from soil humidity and grey elements correspond to waste water.

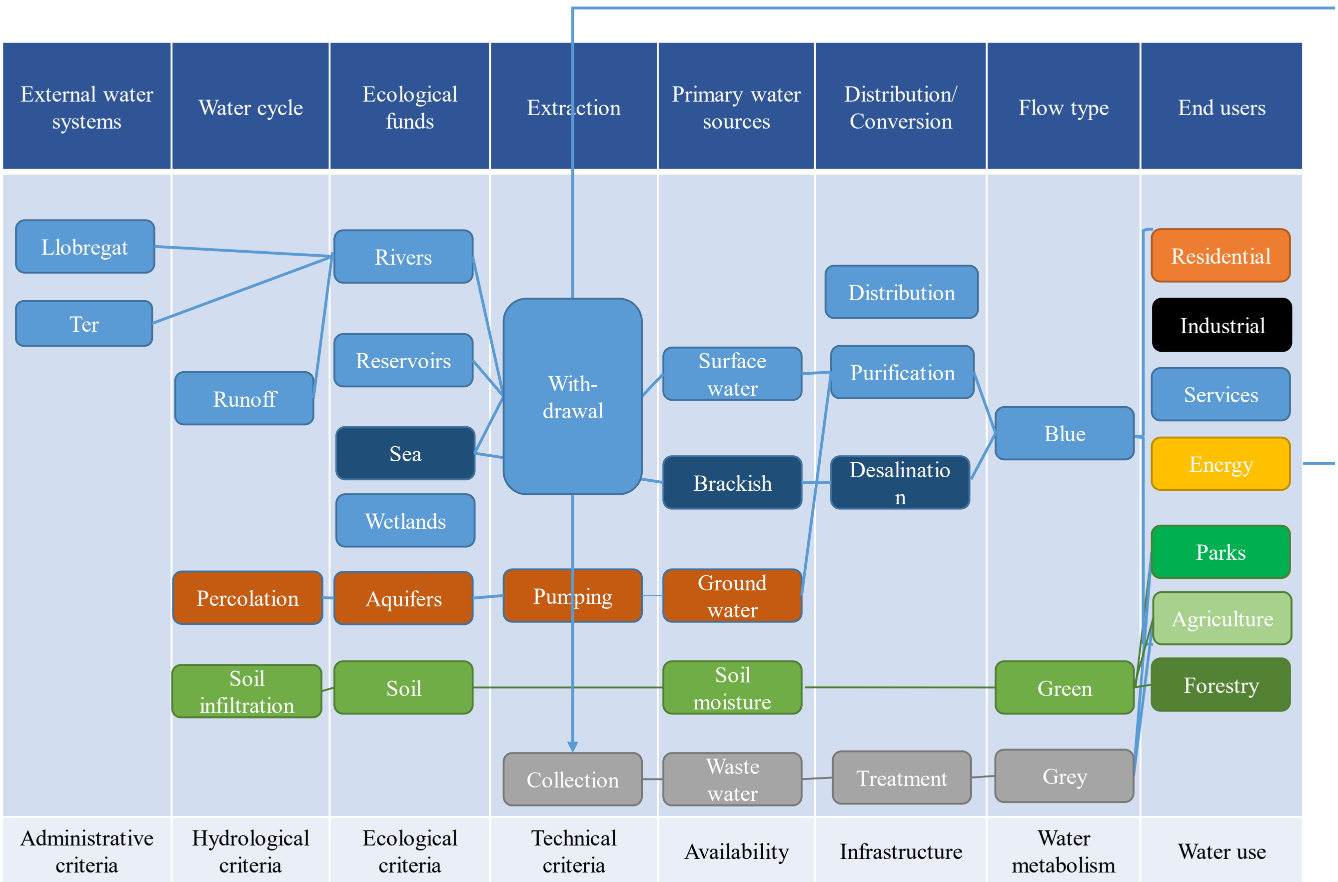


Figure 3. Diagram of the origin of water sources and the relations of the compartments related to water in the Barcelona Metropolitan Area (BMA)

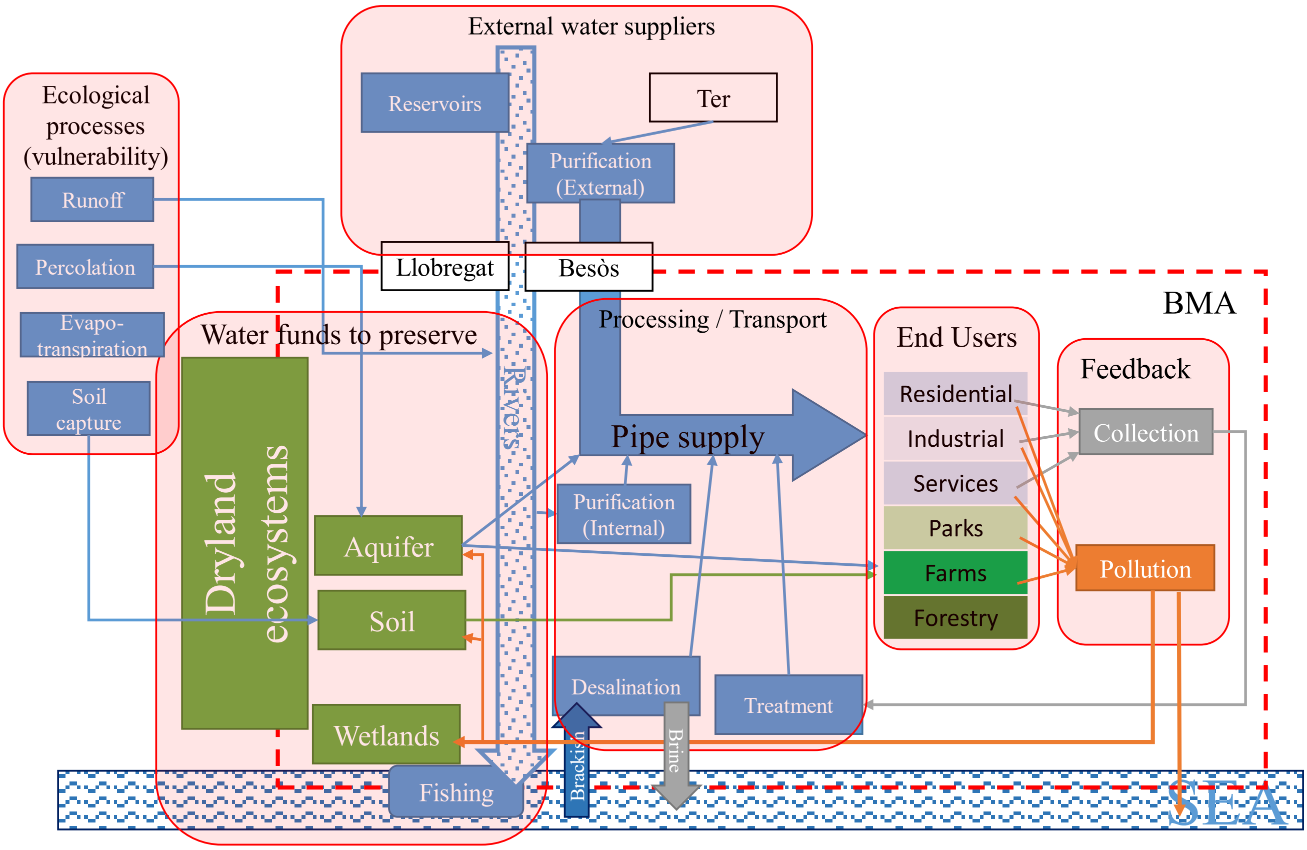
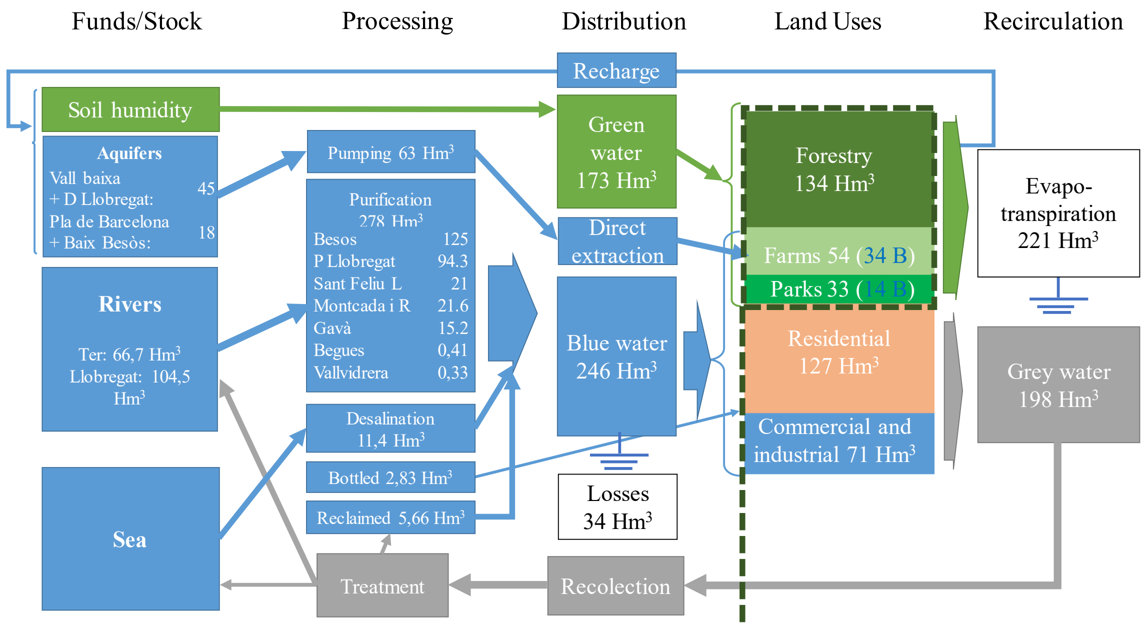


Figure 4. Water flows (Hm^3) in the Barcelona Metropolitan Area (BMA)



Hm^3	Blue Water	Green Water	Total Water
Forestry	0	134	134
Farms	34	20	54
Parks	14	19	33
Total	48	173	221

Green Infrastructure water requirements

Total BMA

Figure 5. Water natural supply and appropriation of blue and green water in the Barcelona Metropolitan Area (BMA)

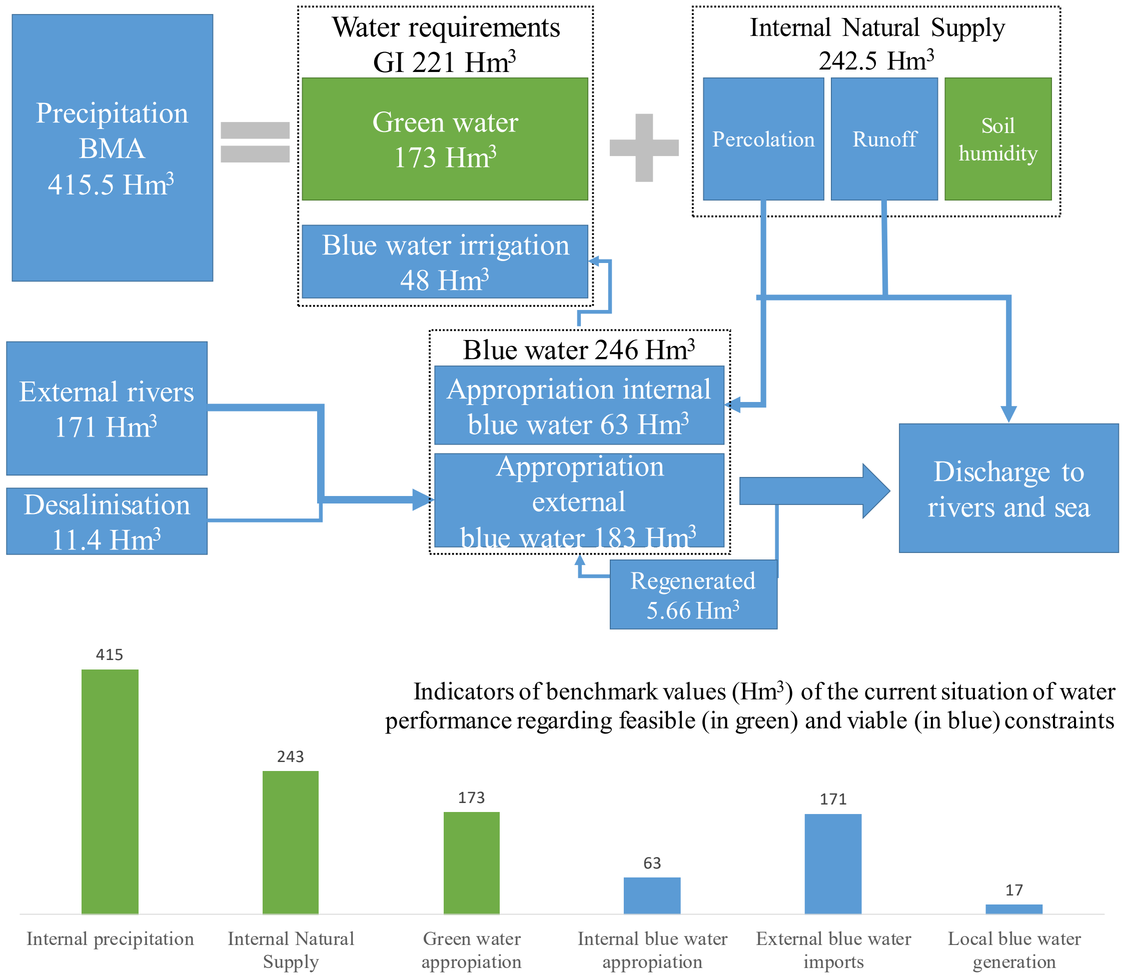
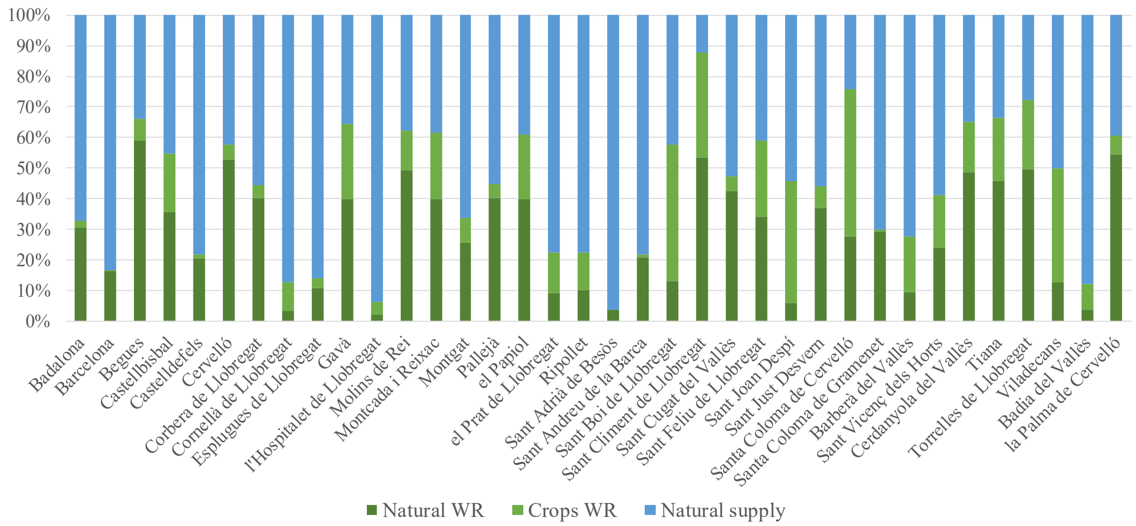


Figure 6. Water natural supply and ecosystem appropriation (%) and volumes of water used (Hm^3) by the forestry and farming sector for the 36 municipalities of the Barcelona Metropolitan Area (BMA)



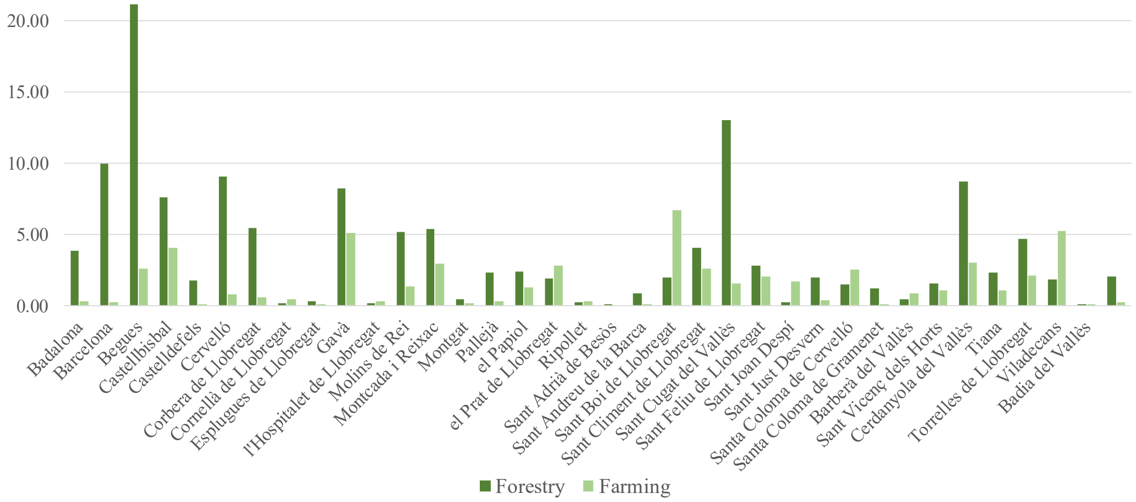
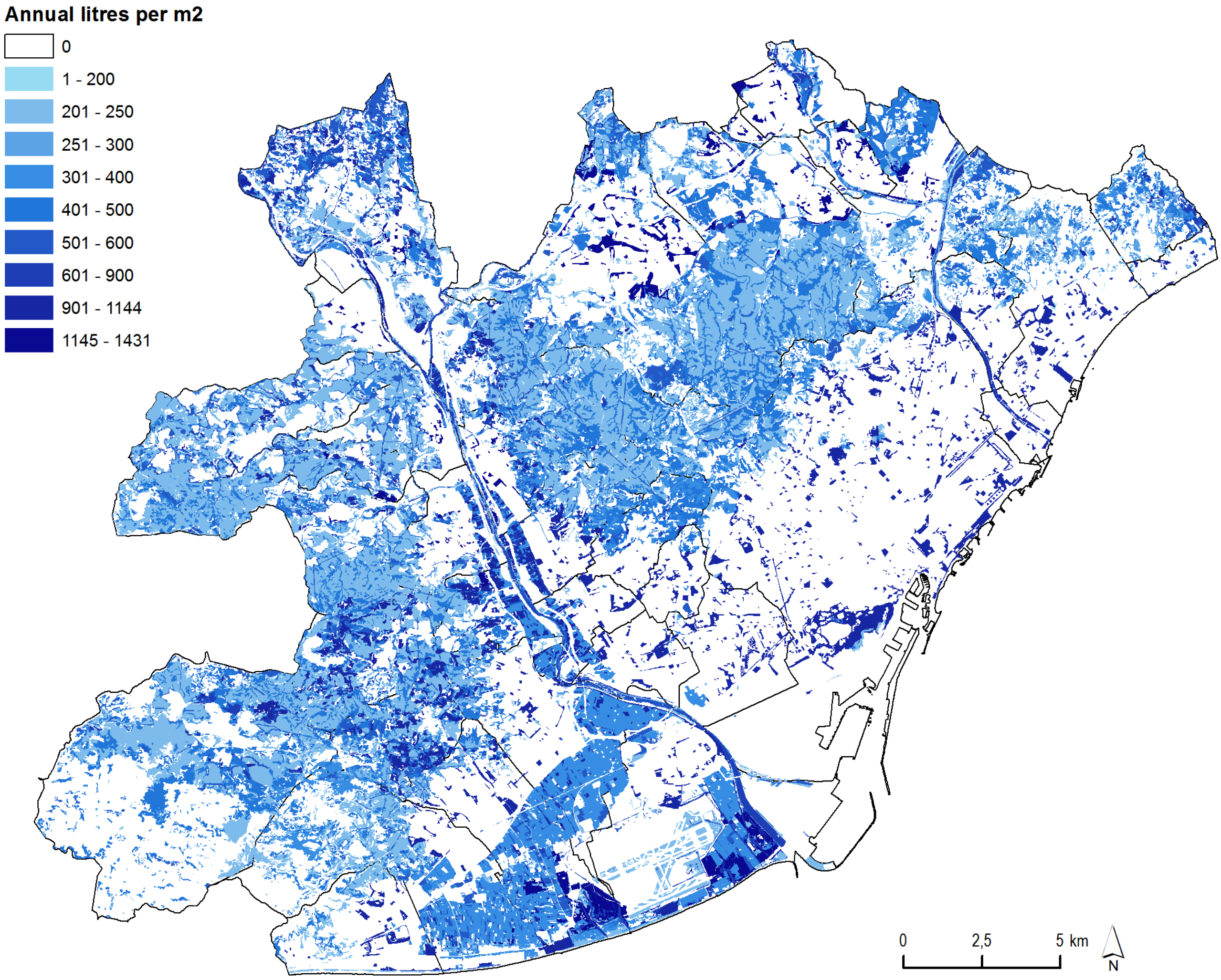


Figure 7. Map of the vegetation water requirement of the green infrastructure of the Barcelona Metropolitan Area (BMA)



Supplementary Material

Figure S1. Diagram of three metabolic flows represented across the same stages