Advances in Water Resources 130 (2019) 258–269

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Relational analysis of the resource nexus in arid land crop production

Violeta Cabello[a,*], Ansel Renner[a], Mario Giampietro[a,b]

[a] Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, 08193, Cerdanyola del Vallés (Barcelona), Spain
[b] Isnstitució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Catalunya, Spain

ARTICLE INFO

Keywords:
Nexus networks
Metabolic processor
Relational analysis
Water-energy-food nexus
Multi-functionality

ABSTRACT

While a large number of descriptive studies have delineated the interlinkages between water, food and energy resources in the last decade, there is still need for systematic conceptualization of resource nexus interconnections. This paper proposes a theory of relational analysis of the nexus based on the analytical concept of nexus networks. A taxonomy of nexus interconnections, detailing sequential and hierarchical connections, is characterized between and amongst the technosphere and biosphere. We illustrate the use of a novel diagnostic tool with regard to its ability to integrate macro-, meso- and microscale drivers of nexus problems. We apply this framework to problems generated by intensive crop production for exportation in an arid landscape (driven by external markets) and sustainable management of water resources (driven by public policies) in a southern Spanish region. We elucidate interconnected causal mechanisms for groundwater overexploitation and profile different social-ecological patterns on a spatially-explicit basis. The proposed approach is capable of accounting for the water-energy-food resource nexus in an integrated and multi-level fashion, addressing the tensions generated by both multi-functionality and resource entanglement in complex social-ecological systems.

1. Introduction

Mainstreamed by international calls for securing resources pressured by entangled global drivers, the water-energy-food nexus notion has gained momentum at an increasing rate in sustainability research and policy agendas. *Interconnections, synergies* and *trade-offs* are common keywords within the nexus concept, where the diversity of definitions has gathered into at least four perspectives: (i) the nexus as governance approaches that seek coordination and harmonization (Nilsson et al., 2012; Weitz et al., 2017); (ii) the nexus as the co-occurrence of resource use in economic sectors and supply chains, also referred to as the *resource-nexus* (Font Vivanco et al., 2018); (iii) the nexus as the interconnection between different resource systems generated by specific activities or technologies (D'Odorico et al., 2018); and, transversally, (iv) the nexus as transdisciplinary and co-production practices in sustainability research (Howarth and Monasterolo, 2017; Scanlon et al., 2017).

Nexus problems have been characterized as types of wicked or post-normal problems underpinned by uncertainty, ambiguity, contested stakes and unpredictability (Harwood, 2018). Furthermore, these nexus situations are argued to be the outcome of co-existing macro-, meso- and microscale processes (Cai et al., 2018), which can be related to the different conceptualizations of the nexus identified above. From a macro perspective, the nexus preoccupation arises from the acknowledgement that economic sectors responsible for resource co-occurrence are governed by different public policies and private markets with 'silo' dynamics frequently expressing conflictive goals (Muranetto and Witmer, 2017; Venghaus and Hake, 2018). Therefore, a need is claimed for 'closing the governance gap' and improving policy coherence (Weitz et al., 2017). Whereas the macroscale is epitomized by this interface between policy and market constraints and economic sectors, the mesoscale is represented by the interface between those sectors and the water, food and energy resource management domains they connect. Resource management domains are associated with regional spatial scales, since they are responsible for controlling the level of extraction of primary resources. On the other hand, economic sectors are networks of entities connecting different regions that metabolize extracted resources along production chains (Franz et al., 2017). Nexus difficulties at this level are encountered in cross-sectoral management approaches when bringing together sectors and managing trade-offs between them (Pahl-Wostl, 2017; Stein et al., 2018). Lastly, at the microscale and somewhat paradoxically, many localized nexus problems have emerged as the result of techno-social innovations aimed at solving the conflict between policy goals (Cabello and Madrid, 2014). Classical examples of nexus problems in this sense include desalination and irrigation efficiency. Innovations related to both of these problems add dependencies on energy resources – such as electrical energy to drive water pumps – to the water-food nexus, thereby increasing the structural complexity from a management perspective. Moreover, as solutions for reducing pressures over fresh water resources emerge, monitoring of

---

[*] Corresponding author.
E-mail address: Violeta.Cabello@uab.cat (V. Cabello).

https://doi.org/10.1016/j.advwatres.2019.06.014
Received 16 January 2019; Received in revised form 25 June 2019; Accepted 25 June 2019

social-ecological interactions such as water withdrawal or pollution are demanded.

The nexus concept thus appears as an indicator of the need to improve our capacity to account for the interconnections between complex social and ecological processes tensioned by multi-level and conflicting drivers. Recent empirical research commences to delineate interconnections as the different causal relations in processes involving more than one resource (Andrews-Speed et al., 2012; Bijl et al., 2018). Yet, whereas relations are the core research object of the nexus concept, little progress towards a categorization and formalization of interconnections has been made. Some consensus has gathered around the differentiation between biophysical connections, coined as the resource nexus, and other social and governance relations (Cai et al., 2018; Galaitsi et al., 2018). Within the resource nexus, a first approximation to categorization is the Font Vivanco et al. (2018) taxonomy of direct, dependent and interdependent relations. Their model shows that the co-occurrence of water and energy along supply chains can be mostly explained by direct extraction or one-way dependencies, while feedbacks appear minor. Their categories, however, account only for interactions amongst economic sectors at the national and global scales. When moving to local and regional contexts, interdependencies are likely to gain relevance following the consideration of social-ecological interactions (Albrecht et al., 2018).

This paper furthers previous efforts in categorizing nexus interconnections by proposing an operational concept of *nexus network*. For this purpose, we draw on ideas from some branches of complexity theory, namely relational analysis (Rosen, 1958, 2005, 2012), hierarchy theory (Ahl and Allen, 1996; Allen and Starr, 2017) and societal metabolism (Georgescu-Roegen, 1971, 1975; Giampietro and Mayumi, 2000). We add to the nexus pathways concept of Vivanco et al. (2018) with a multi-level conceptualization of nexus networks that includes interactions within and between the biosphere and technosphere. This conceptual framework is applied to nexus problems derived from intensive crop production in arid and semiarid landscapes with over-exploited water resources, which often find solutions in energy-intensive technologies. The region of Almeria in South-eastern Spain serves as illustrative case study. The methodological framework Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM, Giampietro and Mayumi, 2000) is applied to quantitatively formalize the network, addressing the following question: why are groundwater resources overdrafted in Almería?

2. Relational analysis of nexus networks

2.1. Theoretical ground

Relational analysis is a variety of complex system analysis that explores the identity of living systems by representing them formally in metabolic networks characterized by the four Aristotelian causes – material, formal, efficient and final (Rosen, 2005). This understanding of relational analysis finds roots in theoretical biology and the seminal work of Rashevsky (1954) and Arbib et al. (1973), furthered by Rosen (2005, 2012) and more recently by Louie (2009, 2013, 2017) into a new conceptual framework to the modeling of living systems within the field of category theory. Following their discourse, relational analysis addresses provocative questions of 'why' by expounding the pluralism of causal relations defined over the components of a system.[1]

The focus of relational analysis thus centers on the organizational unity of the analyzed system, describing the various roles, or functional behaviors, of system components. More specifically, relational analysis views the fuzzy relations between function and structure observed in complex systems as compelling subjects of analysis (Kampis, 1987a, 1987b; Rosen, 1970; Bechtel and Richardson, 2010). In this sense, described functions may be realized – in an impredicative and epistemological manner – by different structural elements. Within the field of hierarchy theory, Allen and Starr (2017, pp.43–67) also elaborate on the impredicative duality of function and structure, to be analyzed over a minimum of three analytical levels within a complex system.

Together with relational analysis, hierarchy theory helps define core characteristics of components in a complex metabolic network. Firstly, system components are defined at the same time as a part (e.g. a liver as organ of a human being) and a whole (e.g. a liver made up of cells). Secondly, as mentioned previously, system components handle the coupling between function and a structure (e.g. the function 'professor' must be realized by a particular material instance, for example, Prof. McGonagall). Thirdly, reflecting back on the Aristotelian building blocks of relational analysis, system components may be arranged sequentially (material entailment) and hierarchically (functional entailment) in the formation of a network. To clarify, a hierarchical disposition of system components represents a chain of definitions of function. Each functional definition of a component provides the final cause or purpose to the realizing structure(s) – thereby its meaning. Each function may be realized by one or more structural components (made of the material cause), expressing their agency (efficient cause) when operating in an admissible environment and following certain patterns or codes (the formal cause).

The final piece of this framework is the concept of societal metabolism, a notion used to characterize the processes of energy and material transformation in a society that are necessary for its continued existence (for an overview of its application to ecological economics see Martínez Alier and Schlüpmann, 1987); for an overview of its application in sociology see Fischer-Kowalski, 1998). The metabolic approach enables the application of relational analysis and hierarchy theory to nexus relations in social-ecological systems. Giampietro (2018a) defines such a system as a set of functional and structural components linked by a set of relations and operating within a given boundary to achieve a shared function (a given final cause). Building upon this definition, the MuSIASEM accounting framework (Mayumi and Giampietro, 2000) has been proposed as one of the available integrative methods for quantitative analysis of the nexus (Giampietro et al., 2014; Keairns et al., 2016; Shannak et al., 2018). In the following section, we add a conceptualization of nexus networks to this framework.

2.2. Multi-level nexus networks

A nexus network can be defined as the set of processes governing the interdependency between water, food and energy within and across a given boundary. As any network, nexus networks are represented with nodes and connecting edges. Nodes refer to specific processes consuming more than one resource and producing good(s) or service(s). In formal, operational terms, we represent these nodes using the concept of the *metabolic processor* (Rosen, 2005, p.250). Most typically, metabolic processors (hereafter 'processors') perform work on a material substrate and transform it into something else performing a function in a complex network. The elaboration of the processor concept into an analytical tool within societal metabolism theory is a remarkable contribution of the MuSIASEM accounting framework (Ripa, 2017; Giampietro, 2018b). In this vein, a processor (Fig. 1) identifies an expected set of relations regarding: (i) a structured process capable of producing a given output or expressing a given function (*n* – 'node' – in Fig. 1); (ii) a profile of inputs and outputs in both the technosphere and the biosphere required for

---

[1] For illustrative example, assume there exists a constituent component A; (i) the material cause of A refers to the material out of which A is made; (ii) the formal cause of A refers to the pattern (form) to which the material cause is required to assume in order to form A; (iii) the efficient cause of A is, in the majority of cases, the agent which transforms the material cause into A (adhering to the formal cause, in abstract terms some function *f*); (iv) the final cause reflects the *for what?* of A.

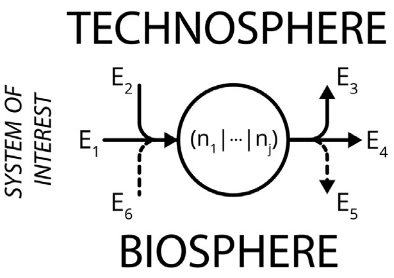


Fig. 1. A canonical processor. *n* denotes a *node* or singular processor and *e* denotes a category of *edges* describing either input or output relations with the technosphere or biosphere.

that purpose ($e_{1\text{-}6}$ – 'edge' – in Fig. 1). In this sense, processors embody the impredicative duality between structure and function of a system component.

Processors such as the canonical processor in Fig. 1 can be connected in different ways in the formation of a nexus network. Fig. 2 presents this point using the same notation found in Fig. 1. In the analysis of social-ecological systems, a minimum of three connection domains should be identified: (i) connections that remain within the socioeconomic realm (the 'technosphere'); (ii) connections that remain in the ecological realm (the 'biosphere'); and (iii) connections bridging socioeconomic and ecological processes (the 'technosphere-biosphere boundary'). In any given nexus problem, the co-occurrence and entanglement of resources implies causal connections within each of these three connection domains simultaneously.

In addition to these three connection domains and pursuing relational analysis, a second dimension is added differentiating between sequential and hierarchical connections in Fig. 2. As already elaborated by Vivanco et al. (2018), sequential connections are material flows between specific activities or sectors therefore modelling expected outputs at a given level of observation. In formal terms, they are one-one or one-many allocations with one-way or feedback direction determined by the material entailment between processors. In contrast to sequential entailment, hierarchical connections are determined by functional entailment. That is, the function to be expressed at one level has been defined as 'useful' (as having a proper final cause) at the hierarchical level directly higher. Hierarchical connections are formalized as many-to-one or many-to-many mappings between system components expressed at different levels of observation.

For instance, one can represent a network of connected food production processes following various stages of production and processing (sequential relations within the technosphere). This sequential pathway may then be scaled up through the various agricultural subsectors, ultimately into the agricultural sector in a given region (hierarchical relations within the technosphere). Alternatively, the same sequential pathway may be scaled up through the different scales of river basins supplying water to the agricultural processors (sequential relations across the technosphere-biosphere boundary). These two example scaling operations are non-equivalent hierarchical mappings of the same set of sequential relations and they enable the answering of different questions about the system under analysis.

As in other system analyses, the specification of a nexus network requires a research question or problem that enables the selection of analytical scales and the delimitation of system boundaries and system components with associated functions within the system. From a societal metabolism perspective, this is equivalent to identifying socioeconomic sectors and their specific activities intertwined with ecological processes within a defined social-ecological boundary. In the logic of analyzing final causes, the functionally defined components at a given level must be further associated to patterns of structural components that are viable within system constraints at a lower level, what is equivalent to specifying hierarchical relations. Following the previous example, the agricultural sector would be split in subsectors (for instance animal vs vegetal production) and subsectors into supply chains that are viable in a given region.

We aim to design a diagnostic tool capable of analyzing the tensions generated by conflictive goals and multi-level drivers. Using a functionally and structurally defined network, these tensions can be described as a problem of multi-functionality. The fact that different system components coexist within a social-ecological system and that their multiple functions need to be sustained while they adapt to external drivers creates many constraints on the type of structural elements that can fulfil those functions. The spectrum of viable solutions to nexus problems is limited in the context of competing drivers and any implemented local solution will transform the network of relations by adding new structural constraints.

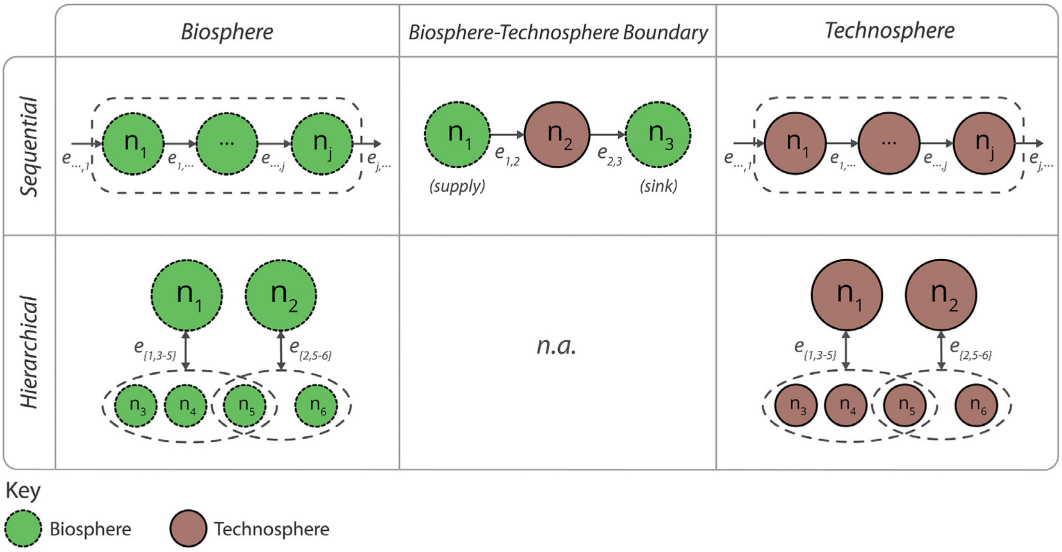


Fig. 2. A taxonomy of nexus interconnections resulting from the combination of the criterion of social-ecological relations and the criterion of sequential-hierarchical relations. *n* (node) denotes a processor, individuated by its index; *e* (edge) denotes a relation (either sequential or hierarchical) between two or more processors, where the first index identifies a source node and the second index identifies a target node(s). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. Formalization of nexus networks

Once the network of metabolic processors is defined in semantic terms, the next analytical step is to instantiate them. In formal terms, a processor is a data array structure that contains information about the profile of inputs and outputs required in a given process. The computational form related to this profile shares a number of similarities with that of Life Cycle Assessment (LCA) (see Heijungs and Suh, 2002).

In relational terms, an j-indexed socioeconomic processor n_j can be formalized as a column-vector, as shown in Equation E1. The elements of this vector, e_1 through e_i, represent for some processor n the set of expected relations defined in intensive terms against a relation or set of relations. Most typically, the relations in a processor are described against just one element (e.g. per unit of a processor output or otherwise immutable quantity such as human activity or land use processor inputs).

$$n_j = \begin{pmatrix} e_1 \\ \vdots \\ e_i \end{pmatrix} \tag{E1}$$

Further, several rowwise partitions are erected in this column-vector. In the most general sense, and following the canonical processor presented in Fig. 1, the relations of a processor e_1 through e_i may be placed in one of four[2] possible categories. The combination of two variables each with two possible values creates these four categories: the relation's *domain* (technosphere or biosphere) and its *orientation* (input or output). The set S in Eq. (E2) lists these two variables and elaborates their possible values.

$$S = \left\{ \begin{pmatrix} technosphere \\ biosphere \end{pmatrix}, \begin{pmatrix} input \\ output \end{pmatrix} \right\} \tag{E2}$$

The last bit of information associated with each relation is its entailment dependency or dependencies i.e. in the case of a singular dependency, whether a cause of one process is produced by or contributes to another process(es). In the case of a singular dependency, we can say that the validity of the first process both depends on and entails the existence of another process(es). Fig. 2 depicted the various entailment dependencies possible in our relational analysis.

Processors may, therefore, be represented as column-vectors (Eq. (E1)) partitioned along the elements of the set S (Eq. (E2)). The concatenation of all processors described as sparse column-vectors then provides the 'dataset' describing the system of interest for the purposes of the analysis, as shown in Eq. (E3). It should furthermore be noted that the description made by Eq. (E3) represents the most basic categorization possible. An effective analysis necessarily includes additional subledgers dependant on the goals of the analysis. For example, in analyses of societal metabolism, an additional subledger differentiating between fund, flow and stock resource is typically regarded as an essential relation refinement (Georgescu-Roegen, 1971).

$$\left(n_1 | \cdots | n_j\right) = \begin{pmatrix} e_{1,1} & \cdots & e_{1,j} \\ \vdots & \ddots & \vdots \\ e_{i,1} & \cdots & e_{ij} \end{pmatrix} \tag{E3}$$

Generally, processors are stored in the dataset in intensive (unitary) terms. To maintain validity, care must be taken to relate intensive representations with their original external reference. In an analysis of a system of interest, the set of intensively described processors may be proportioned by the size of supply (vector Q_s), or by any other variable against which relations are defined, to fulfil demand (vector Q_d). In the context of this work's case study, supply vector Q_s would include mass quantities of e.g. Almonds and Vegetables; demand vector Q_d would include various resource demands e.g. land (area) requirement and groundwater (volume) requirement. In this vein, processors arranged in a network may describe in intensive and/or extensive terms the complete set of sequential and hierarchical relations within and between the technosphere and biosphere. These two different sets of numerical representation provide two different key types of information about the system of interest (King and Carbajales-Dale, 2016). Eq. (E4) formalizes the relation between intensively defined processors, supply and demand. The formalism works for diagnostic analyses as well as anticipatory analysis. In an anticipatory analysis, changes in resource demand may be estimated from anticipated changes in (i) technical coefficients (intensively defined processor data) e.g. because of technological change; and (ii) supply e.g. following demographic projections.

$$\left(n_1 | \cdots | n_j\right) Q_s = Q_d \tag{E4}$$

3. Application to the nexus in arid land crop production

In this section we illustrate the process of building a nexus network for analysing the tension between intensive export-based crop production and sustainable management of water resources in the province of Almería in South-eastern Spain.

3.1. Framing the problem

Almería is one of the driest regions in Europe (average annual rain 200–600 mm). At the same time, it represents one of the largest intra-European suppliers of fresh vegetables, exporting up to 64% of their overall production. Main importing countries are Germany (30%), France (16%), the Netherlands (12%), UK (11%) and Italy (7%) (Agencia Tributaria, 2013). Other major land uses for crops are olive groves, almonds and varieties of citrus. Agriculture sustains 8% of the employment in the region and 2.4% of its GDP (Junta de Andalucía, 2013). Contrary to other intensive exploitation systems in Spain, land property is highly distributed with an average farm size of 2 to 3 hectares and where most farmers are associated to cooperatives for marketing purposes (Varela-Martínez et al. 2016). The region is a renowned example of unsustainable exploitation of groundwater resources in Spain, with many aquifers classified as severely overexploited and/or polluted according to the European Water Framework Directive (WFD) assessment. The European WFD also mandates that all European water bodies must recover to a 'good status', a mandate expressed in terms of 'environmental goals' defined by the year in which a good status shall be recovered following the implementation of new management measures. Fig. 3 depicts these goals for the Almería region.

Framing the nexus problem, a macroscale tension arises from the goals of water policy, which require a reduction of the pressures over water resources, and European food markets eager to absorb the increasing local production. At the region level, the problem translates into the question of how to re-organize relations between agricultural and water management regimes. Agriculture is responsible for 80% of the water usage, 62.5% of which is groundwater (Junta de Andalucía, 2015). The main solutions on the table so far have been the utilization of alternative water resources, desalination and reclamation, or external transfers as substitutes for groundwater and the improvement of irrigation efficiency. A decade later, overdraft rates are not reported to decrease and the contribution of these innovations to the stated purpose is unclear. Using the framework described above, we build a nexus network to provide a relational analysis of the aquifer over-exploitation phenomena.

As mentioned, relational analysis focuses on multiple causality in complex problems by elucidating interconnected functions. Clearly, addressing the question of why aquifers are overexploited in Almería can be answered from different lenses. For instance, a governance and power relations reading would illuminate one sort of relevant responses regarding the key actors involved in the problem and their interconnections. However, this paper focuses on the metabolic reading of the nexus. That is, on the type of answers provided by sequential (material) and hierarchical (functional) entailments between metabolic processors. We

---

[2] Relations within the system of interest are always within the technosphere, an observation which explains how the six categories in Fig. 1 may be reduced to four at this stage of the formalization.

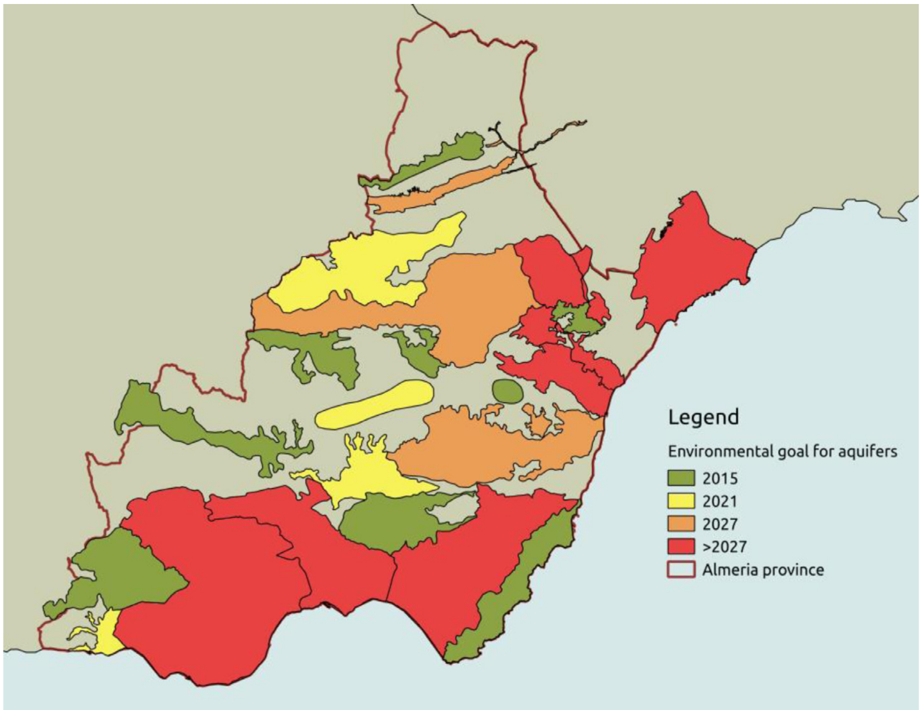


Fig. 3. Map of aquifers in Almeria classified according to environmental goals in water districts management plans 2015–21 (Junta de Andalucía, 2015; Gobierno de España, 2015). Environmental goals are defined by the year in which a good status shall be recovered. Aquifers coloured in green were assessed as being in good status in 2015. Those in yellow (good status to be achieved in 2021), orange (in 2027) or red (in undetermined horizons later than 2027) have been assessed as being in less than good status, meaning they are quantitatively and/or qualitatively over-exploited. Quantitative impacts are specified in Figure 5. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

assume the view that the ultimate final cause for over-drafted groundwater resources in present-day Almería is the maintenance of an agricultural economic model based on valuable crop exports. Understanding the other causal mechanisms for the overexploitation phenomena requires a threefold analysis. First, it is necessary to understand what farming systems are driving water demands. Second, it is necessary to look at the role of groundwater within the overall pattern of water resources supplied to those farming systems by irrigation organizations. Lastly, it is necessary to contextualize withdrawals in the hydrological balance of the different aquifers.

3.2. Building the network

Considering the whole region of Almería as a social-ecological system, a multi-level nexus network was defined connecting key components of food and water management domains identified above (Fig. 4). At the top analytical level (1), these domains are responsible for organizing the implementation of public policies, programs or strategic goals for those sectors, posing top-down constraints over the behavior of lower level system components. As mentioned, bottom-up constraints can be uncovered by adding levels of functional-structural metabolic processors to the network. In this vein, the agricultural sector has been disaggregated into irrigation areas as the organizational units of water management in agriculture, and further into farming systems and even further into the different crops produced in each of those farming systems. On the other hand, sequential connections relate functions within the same level adding more constraints to the network in terms of multi-functionality. In our network, sequential linkages are established within components of the water management system, namely water bodies, water suppliers and irrigation areas as water users.

3.3. Operationalizing the network

As explained in Section 2, the methodological approach proposed in this paper uses the numerical structure of processors to quantify nexus nodes and relations. For this purpose, one must identify physical instances matching the categories of system components, quantify processor variables and profile representative types of processors out of

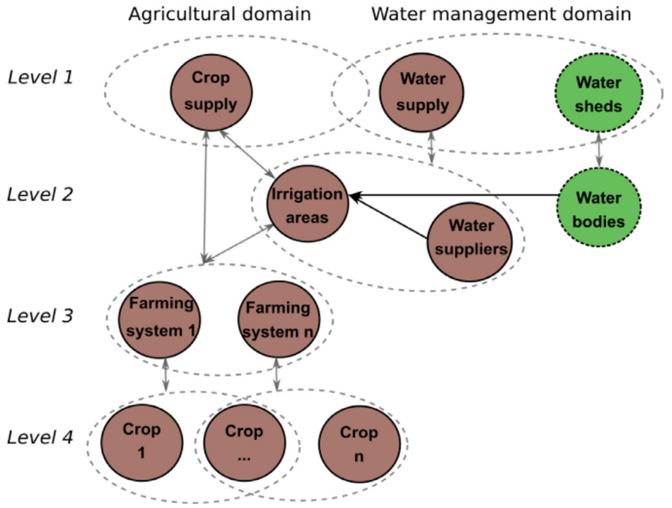


Fig. 4. Definition of a multi-level nexus network linking crop supply and water management in Almería. Black arrows represent sequential connections while grey arrows represent hierarchical connections. For a full description of categories please refer to the appendix and the databases. Color key is shown in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

them. The most standard procedures are either data-driven (e.g. sample a population and cluster it in typologies) or semantic-driven approaches (e.g. pre-define typologies and sample representative instances). For the Almería case, we followed a mixed approach. Within the agricultural domain, we defined typologies of crop production processes and farming systems through a review of previous studies and techno-agronomic reports (García-García et al. 2016; Varela-Martínez et al. 2016) and the analyses of land use data for different crops petitioned from the Andalusian Agricultural Administration. On the other hand, available georeferenced datasets for water system components in river basin management plans (Junta de Andalucía, 2015; Gobierno de España, 2015) enabled the characterization of the full population of water bodies and irrigation areas. Crop data was only provided for the productive year 2012–2013 whereas data on water extraction and use is available as an annual average for the 2010–2015 management period. Therefore, the analysis is bound to a single snapshot of the annual metabolism of the system without addressing its time evolution.

Processors variables were populated with data gathered from different secondary sources and integrated in two databases describing the crop production and the water management domains. Variables were scaled from lower to upper levels in the network according to the land use patterns described across levels. Structured and documented datasets and R code for scaling operations are published in a Zenodo[3] repository and the data management process from collection to visualization is thoroughly described in the Appendix. Given the diversity of data sources and their production methods, mostly based on estimations rather than accurate measurements, the technical and methodological uncertainty associated to the datasets is notable. For the purposes of this paper, we restricted data analysis to the most trustful variables used by public institutions in their management plans. Further efforts in reliable data production for robust integrated assessments of nexus interconnections are needed in the future.

To address the proposed research question, we provide a diagnostic analysis consisting of the interconnected visualization of some variables in food and water processors at different levels in the network, namely, withdrawal rates from aquifers by different irrigation areas (level 2), patterns of water resources use in irrigation areas (level 2), patterns of land uses in irrigation areas (levels 2/3/4) and crop production factors in different farming systems (levels 3/4)). Groundwater availability and the derived Extraction Index[4] are used to check the sustainability of different water-food nexus patterns against quantitative impacts on aquifers. For analytical purposes, the processors describing the 16 irrigation areas are clustered into 7 typologies based on their pattern of farming systems (level 3). For this purpose, profiles associated with quantitative criteria on land use were defined through a qualitative analysis of most representative patterns and the 16 irrigation areas were coded accordingly (see Table A3 in the Appendix for further explanation and Ouput/ClusterData.xlsx in the data folders for assignation of irrigation areas to each cluster). Processors variables, including withdrawals from aquifers, were aggregated for the obtained categories and selected indicators calculated. This clustering enables profiling several typologies of social-ecological patterns on a spatially explicit basis as presented in the next section.

4. Results and discussion

4.1. Why are aquifers overdrafted in Almería?

We are now in the position of providing a quantitative relational analyzes of our nexus problem. Fig. 5 presents the geographical display of the clustered irrigation areas overlapping aquifers in the region classified by their Extraction Index. Fig. 6 visualizes the above described variables of several connected processors within the food and water regimes. According to the water districts management plans, 12 out of 27 aquifers in Almería show an extraction index over 0.8, meaning their exploitation rate is considered unsustainable. The spatial distribution of this index reveals a certain predominance of high extraction rates along the coastline as compared to inner rural areas. These rural irrigation areas are to a large extent dominated by low intensity almond and olive production (irrigation area type IA4, farming systems F5 and F7 in Fig. 6(2)). Connected aquifers show either low or moderate extractions rates (0.8–1.1) in those areas with presence of vegetables or lettuce production in open fields (IA2 and IA3). For those aquifers with extraction index over 1.1, Fig. 6(1) presents the annual volume of extraction split by type of irrigation area (IA).

In absolute terms, most groundwater over-extraction in Almería is incurred from three aquifers (011, 012 and 013) by three irrigation areas clustered in IA1. These areas, populated by greenhouse farming systems (F1 in Fig. 6(2)), grow a vast amount of fresh vegetables and elicit the highest rates of labor and gross value-added generation. As observed in Fig. 6(3), the IA1 cluster has introduced more alternative water resources than the other IAs, although they still represent a small share of the total water used.

In relative terms, the aquifers showing the highest extraction indices are associated with other types of farming systems, predominant in clusters IA5 and IA7. IA5 is represented by a single irrigation region occupied by olive groves in hyper-intensive production mode (F6 in Fig. 6(2)). This novel system has rapidly extended due to its larger margin of benefits as compared to intensive olive production and spurred by public subsidies (F5). Whereas its contribution to annual overall crop production in the region is minor (Fig. 6(4)), it consumes almost exclusively groundwater from aquifers with very low annual availability (007–009). On the other hand, cluster IA7 gathers two large irrigation areas representing the second most relevant contribution to regional water demand and crop production after IA1 (Fig. 6(3) and (4)). It combines three main types of farming systems producing mixed vegetables in open fields, with lettuce and citrus (F3, F4 and F8 in Fig. 6(2)). These farming systems show middle intensities of labor and gross value-added generation. Water resources in these areas blend groundwater from over-drafted aquifers with desalinated water and an important share of external transfers. Even so, current withdrawals contribute to surpass the very low availability rates in five aquifers (001–008).

From the previous analyses we can conclude that the answer to the question of why aquifers are over-drafted in Almería is at least twofold. On one hand, the profitable greenhouse economy has very large demands of water so far fulfilled mostly with groundwater. On the other hand, we find a large area of less water demanding farming systems relying on aquifers with very limited water available. Implementing water policy objectives requires ratcheting withdrawals down below availability (grey reference line in Fig. 6(1)). The volume of these reductions might not look dramatic in absolute terms, but it is an important fraction of water supplies for several irrigation areas as observed in Fig. 6(3)).

4.2. Discussion

In the absence of an effective harmonization between water and agricultural policies in the EU (Söderberg, 2016), the tension between environmental policy objectives and market demands in relation to crop production in Almería could be addressed by its: (i) final causes (e.g. what if the agricultural model in Almería is transformed to meet sustainable aquifer yields?); (ii) material causes (e.g. what if the available groundwater is increased?); (iii) formal causes (e.g. what if the pattern of supplied water resources is transformed?); or (iv) efficient causes (e.g. what if farming systems adapt to reduce their water demand?). These four categories of causal relations span both structural and functional considerations, and may be combined in the search for robust solutions.

With coastal irrigation areas showing high irrigation efficiency rates and with the increment of external transfers blocked by social conflicts,[5] the main strategy implemented over the past decade in the analyzed irrigation areas lay in increasing the production of alternative water resources in order to replace groundwater (i.e. a formal cause strategy). However, as observed in our analyses, the penetration of these water supplies is still minor in most irrigation areas. Discussed reasons for this

---

[3] https://zenodo.org/record/2539219#.XDx9PRBRcVs.

[4] Under the Water Framework Directive, the Extraction Index is calculated as the ratio between annual withdrawals and available groundwater.

[5] The two external transfers in the province, Tajo-Segura and Negratin-Almanzora, are associated with noteworthy socio-environmental conflicts in the origin basins (Hernández-Mora et al., 2014).

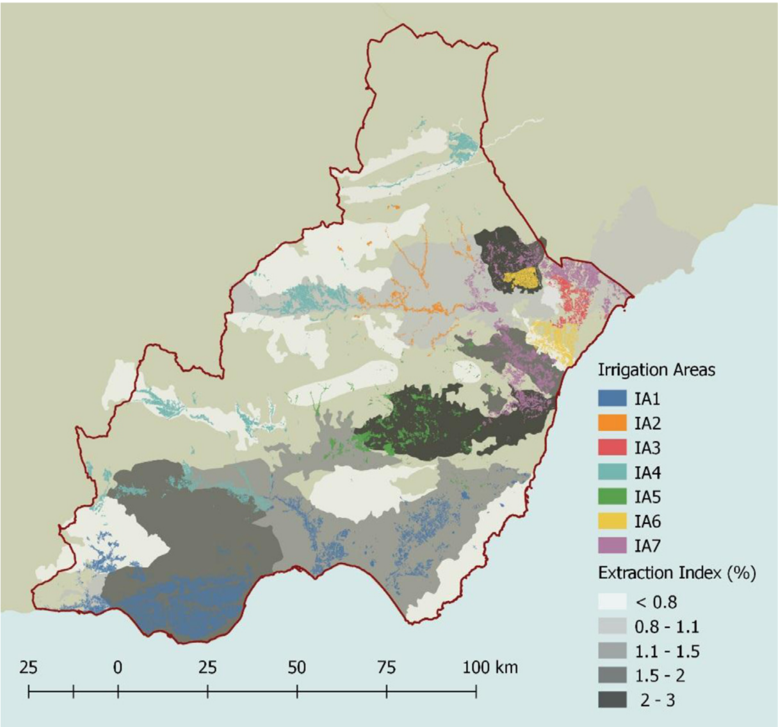
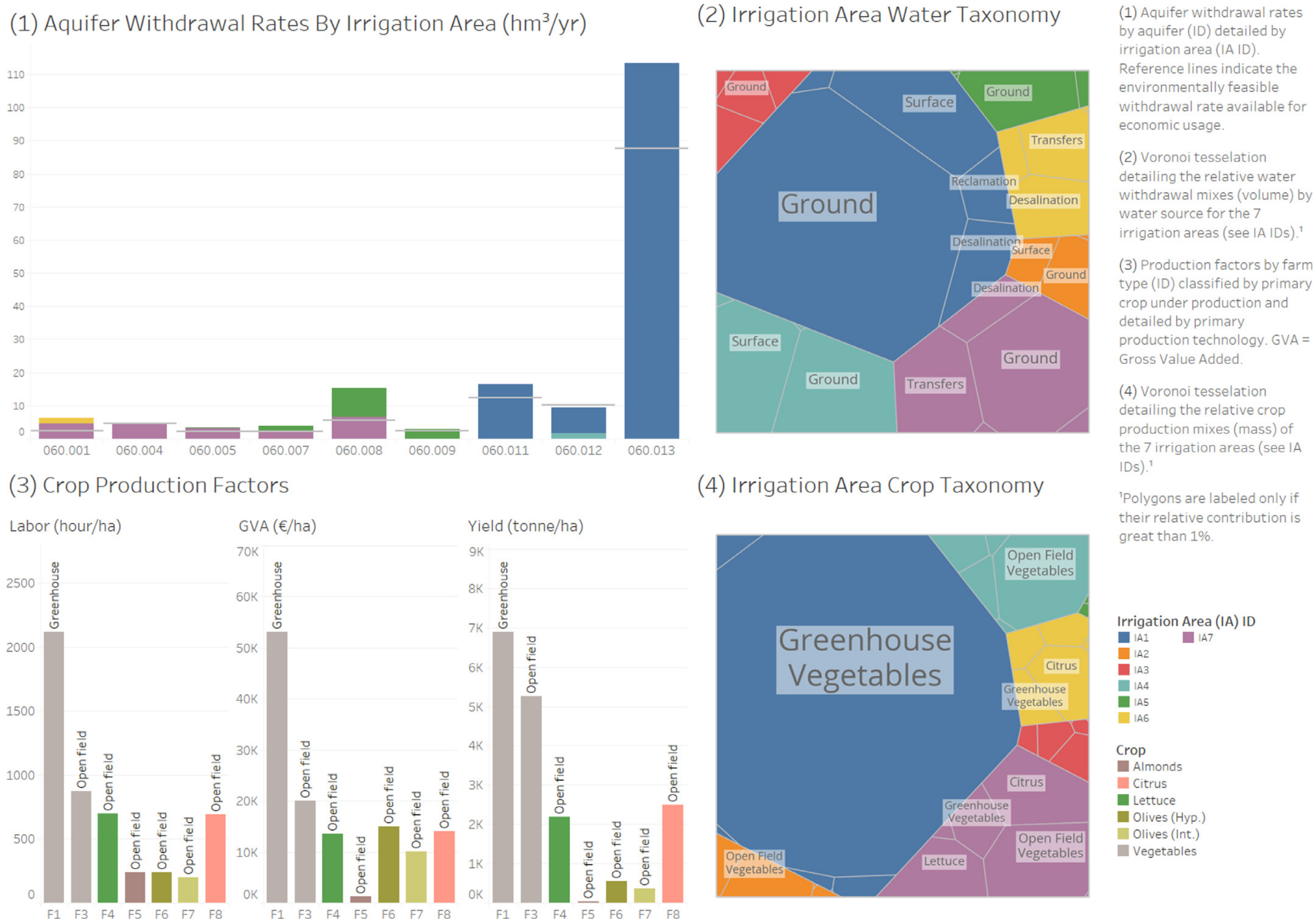


Fig. 5. Map of clustered irrigation areas overlapping relative withdrawal for agricultural purposes in Almería. An Extraction Index over 0.8 is deemed unsustainable under the Water Framework Directive. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



(1) Aquifer withdrawal rates by aquifer (ID) detailed by irrigation area (IA ID). Reference lines indicate the environmentally feasible withdrawal rate available for economic usage.

(2) Voronoi tesselation detailing the relative water withdrawal mixes (volume) by water source for the 7 irrigation areas (see IA IDs).¹

(3) Production factors by farm type (ID) classified by primary crop under production and detailed by primary production technology. GVA = Gross Value Added.

(4) Voronoi tesselation detailing the relative crop production mixes (mass) of the 7 irrigation areas (see IA IDs).¹

¹Polygons are labeled only if their relative contribution is great than 1%.

Fig. 6. Quantitative relational analysis of aquifers overdraft driven by crop production in Almería. Color codes for sub-figures 1, 3 & 4 indicate the cluster of irrigation areas as in Fig. 5. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

outcome include the combination of the high energy cost of related technologies and the context of increasing electricity prices while lowering crop prices[6] (March et al., 2014). This burden is more significant for farming systems other than greenhouses given their more limited margin of benefits. As a result, and looking into the future, either new strategies should be considered or the crop production function of Almería is likely to be forcibly altered.

Our diagnostic analysis shows three social-ecological patterns involved in the overdraft phenomena, namely: (i) intensive greenhouses – withdrawing very large quantities of water; (ii) hyper-intensive olives – drawing from aquifers with extremely low availability; and (iii) mix of open field fruits and vegetables – drawing from aquifers with extremely low availability. These clusters of WEF interconnections face different economic and biophysical constraints that may require diverse adaptive pathways. The multiple ways in which these changes may unfold open a space for simulation and scenario analysis in future research. Our nexus network can be expanded to appraise the viability of alternative solutions capable of maintaining socially desired system functions.

5. Conclusions

Nexus research has mobilized a myriad of existing methodological approaches, and emphasized interconnections as its core research object. This paper furthers these efforts by proposing a theory of relational analysis of nexus networks and a taxonomy of interconnections. We argue for the need to attend to competing drivers of nexus problems at different scales and to social-ecological interactions. Nexus networks are conceptualized in a multi-level fashion that addresses cross-scale feedbacks in terms of bottom-up and top-down constraints to multifunctionality. This is illustrated in an application to nexus problems generated by intensive export-based crop production in conflict with sustainable management of water resources. The scale where this tension is generated is European while regional solutions do not attend the diversity of water-food management patterns and increase nexus interdependencies. The analysis reveals several interconnected drivers of the aquifer overdraft phenomena, at different analytical levels but also in different geographical locations, proving the usefulness of the proposed diagnostic tool. The research nonetheless is limited to a single snapshot and improved time-series are needed for more conclusive results. As signaled in many other nexus papers, existing data sources face problems of methodological and technical uncertainty and further coordinated efforts are required if the nexus is to become a useful science for policy approach. Future advances shall be directed towards (i) embedding the tool in larger extended peer research processes where to implement quality assurance and uncertainty management protocols; and (ii) anticipatory analysis in the assessment of the option space for accommodation of new top-down functional constraints or bottom-up structural transformations of WEF interconnections.

Acknowledgments

The authors are grateful to project partners for their useful reviews and support to this research, especially to Dr. Carmela Iorio for providing guidance on the clustering process. This article reflects only the author's view. None of the funding agencies are responsible for any use that may be made of the information it contains.

Funding

This research has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 689669 corresponding to the project Moving Towards Adaptive Governance In Complexity: Informing Nexus Security (www.magic-nexus.eu); the Spanish Ministry of Education, Culture and Sport (FPU15/03376); the Spanish Ministry of Science, Innovation and Universities, through the "María de Maeztu" program for Units of Excellence (MDM-2015-0552)].

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.advwatres.2019.06.014.

Appendix: Data management

A key contribution of this paper is the methodological development of a data modeling structure for relational analysis of a WEF nexus network with entangled food and water supply. A database per resource domain, one for agriculture and another for water, has been populated with processor data describing network components and their relations for the province of Almería (Spain). In fulfilment of the open access requirements of our funding body European Union's Horizon 2020 Research and Innovation Programme, data has been made available under the license Creative Commons Attribution 4.0 International in Zenodo repository: https://zenodo.org/record/2539219#.XDx9PRBRcVs

As an integrated accounting method, the proposed numerical structure of processors requires collecting and integrating data from multiple data sources. This Appendix describes the data management process from data collection to visualization.

A.1. Sampling, data collection and validation

Data was collected between March and June 2018 from various secondary data sources and direct petition to public administrations. In general, we found water datasets better documented and accessible than agricultural datasets. In what follows, we explain the processes of sampling, definition of variables, data collection and validation used to produce the two databases serving as inputs to the quantitative analysis.

(a) The agriculture database (Input/CropDatabase.xlsx)

Survey sampling

This database contains data on processors describing system components within the agricultural domain. These components are hierarchically organized in our network (Fig. 4 of the paper), from level 4 (L4) describing types of crop production processes, to level 3 describing farming systems (L3) and level 2 (L2) describing irrigation areas. Level 1 (L1), referring to the whole irrigated crop production system in Almería, is derived from previous levels through scaling operations.

In the absence of available data on the full population of farming systems, we worked with representative typologies for characterizing processors at L4 and L3. Besides the analysis of land use data, data informing the decisions for which typologies should be included was obtained from a review of grey literature and techno-agronomic reports describing local systems of production (Tolon-Becerra et al. 2013; García-García et al. 2016; Varela-Martínez et al. 2016).

Starting with L4 on crop production processes, data was petitioned from the Andalusian Agricultural Administration by phone to its office in Almería and followed up by email.[7] Land use data on irrigated crops

---

[6] The average energy costs in the region range from 0.88 kwh/m^3 for groundwater pumping, to 4.5 kwh/m^3 for desalination and to 1.66 kwh/m^3 for wastewater reclamation. Over the last years, farmers in the region strongly championed for subsidies to desalinated water, so far begetting little echo in public authorities.

[7] For the province of Almería, data petitions contact is: <estadistica.al.capder@juntadeandalucia.es>.

Table A1
Categories for crop production processors (L4 in the network).

Crop category	Greenhouses MC1	Greenhouses MC2	Open fields intensive	Open fields hyper-intensive
Fresh vegetables	Pepper	Aubergine	Broccoli	
	Tomato	Cucumber	Lettuce	
	Watermelon	Green beans	Green beans	
	Zucchini	Melon	Melon	
		Pepper	Pepper	
		Tomato	Tomato	
		Watermelon	Watermelon	
		Zucchini	Zucchini	
Oil crops			Olives	Olives
Fruits			Almonds	
			Citrus	

in the different agricultural management units (to a large extent overlapping irrigation areas in the region) was requested for the time series 2010–2015. Out of those years, only data for the production year 2012–2013 was provided. For this reason and considering the absence of available time series for other variables in the crop production processors, the analyzes was restricted to a single annual snapshot. From all irrigated crops grown in the season 2012–2013, we selected the most representative ones based on two criteria:

- Those crops producing more than 10,000 tonne or occupying more than 5000 ha in the selected year;
- In significantly different production systems in terms of yielded tonne/ha*year, namely: greenhouses with two cropping periods (MC2), greenhouses without crop rotation (MC1), open fields with intensive production and open fields with hyper-intensive production.

The resulting list of 24 crop production processors is shown in Table A1. Crop categories correspond to those in the provided dataset and represent averages for several species. For instance, citrus includes different types of lemons, oranges and mandarins.

Defined with a similar mixed procedure of land use and literature analyses, the sample for L3 includes 8 typologies of farming systems showing significantly different patterns of crop production processes. On the other hand, spatial data on irrigation areas (L2) is publicly available in the management plans of the two river basins over which the region is hydrologically divided (Junta de Andalucía, 2015; Gobierno de España, 2015). Therefore, the full population of 16 irrigation areas was sampled.

Definition of variables for characterizing processors and their relations

Processors in this database contain variables characterizing the input-output of agricultural production at the different analytical levels. These variables, and therefore the column-vector structure of processors, may vary with the level of observation. For instance, crop production processes are characterized through variables such as water and different nutrient requirements or crop yield, while farming systems processors include other input variables such as the total use of fertilizers, pesticides or plastics.

Because of the lack of available data on yields at different analytical levels, all variables are intensively defined per hectare of land used. Hierarchical connections between components are therefore operationalized in terms of land use patterns described across levels. No sequential connections are considered for the crop production system.

Data collection and validation

Input data for processor variables were collected from secondary data sources, previous studies or reports. Data sources vary depending on the variable and are all indicated in the database (see 'data_source' column in processors sheets and 'dataset_key' sheet for references). Most gathered data are estimations obtained through different methods as explained in the 'Comments' column in each dataset. Some variables were produced through simple modeling techniques as in the case of fertilizer use (calculated using the guidelines set by the Spanish Ministry of Agriculture) and water footprints (calculated in previous studies using standardized modeling procedures). Other data are statistical estimations developed by public institutions based on a number of assumptions, such as production ratios, water uses or labor requirements. They were accessible in online data portals, management plans and reports. Lastly, measurements of real instances were only found in land use data obtained through GIS methods.

The methodological and technical uncertainty associated to most of the above described data production methods is noteworthy. The lack of a systematic accounting of environmental and social variables in agricultural statistics, especially of water-related variables, hinders the potential of the proposed analytical tool and the capacity to produce meaningful assessments of the sustainability of nexus interconnections. This is an open discussion within the nexus research community that needs to further involve public administrations and their statistical offices at all scales of resource governance.

(a) The water database (Input/WaterDatabase.xlsx)

Survey Sampling

This database contains data on processors describing system components within the water management domain, namely irrigation areas as water users, water providers and water bodies. Water suppliers are desalination and reclamation plants, plus two external water transfers. These components are sequentially connected in our network.

Contrary to the agricultural domain, water management districts have georeferenced datasets locating system components. Therefore, we were able to include the whole population in the database with the exception of water suppliers that were characterised as typologies based on different technologies.

Definition of variables for characterizing processors and their relations

Processors for irrigation areas within the water domain split their water requirements in the pattern of water resources fulfilling those requirements. On the other hand, processors describing water bodies include their inputs and outputs of water as expressed in their annual hydrological balance. Lastly, water suppliers include the total supply capacity, the annual water supply and the ratios of electricity consumption.

Sequential connections in this database refer to the different water flows from different suppliers and/or water bodies to the irrigation areas. They are expressed in extensive terms (Hm^3/year).

Data collection and validation

Data was gathered from the websites of the two water districts in which the region of Almería is divided: the Andalusian Mediterranean Basins Water District (Junta de Andalucía, 2015) and the Segura Water District (Gobierno de España, 2015). Georeferenced datasets were publicly available in their Spatial Data Infrastructures. However, most data for characterizing processors variables had to be extracted from tables in *.pdf documents of their current management plans.

River basin districts in Spain do not perform an annual accounting of actual water uses. Available data refer to estimated average annual

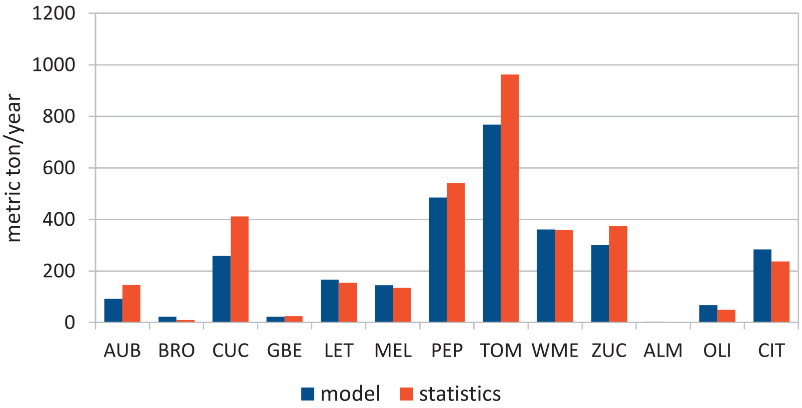


Fig. A1. Calculated vs. statistical values for the total production of different crops in Almería for the year 2012/2013.

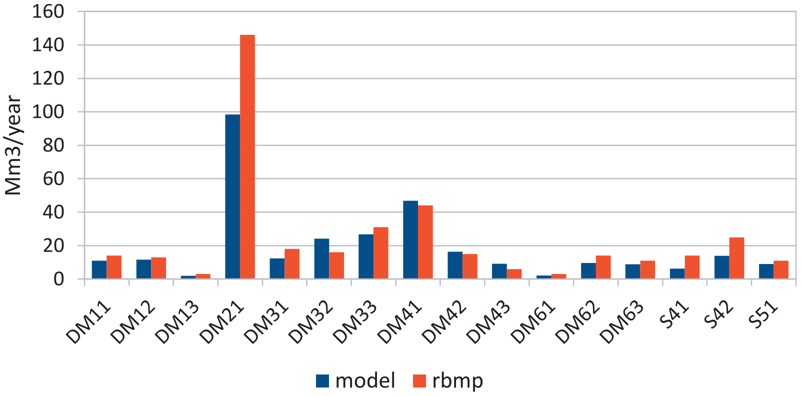


Fig. A2. Calculated vs. river basin management plans (rbmp) values for gross water use in irrigation areas in Almería, average for the years 2010–2015.

water balances for the period 2010–2015. Despite the obvious uncertainty associated to an estimated five-year average, we consider this data source more reliable than those of agricultural databases because it is the baseline information used by water districts for the management period 2015–2020.

A.2. Data organization and processing

Input database organization

The two databases are organized in a similar structure that consist of the following datasets:

- Metadata, including the description of workbook sheets.
- Acronyms: list of acronyms used in all sheets.
- Datasource_key: references and links to data sources.
- Parameters: parameters used for estimations or up-scaling of variables.
- Instances: list of research objects with external referent in the case study.
- Relations: input data describing either sequential or hierarchical connections.
- processors_X: series of sheets containing input data for processors describing network components. Each dataset includes interface data classified along the categories defined in Section 2 of this paper (four or more categorical variables plus the numerical continuity), geographic and temporal scales, data sources and comments documenting relevant information on estimation procedures or data sources.

Data processing

Processor datasets in input databases contain only those variables that are newly defined for each component (properties that cannot be derived from a hierarchical relation). The rest of variables were aggregated from lower to upper levels, through linear or non-linear transformations. The scaling was perform using R scripts, for which the code may be found in the data folder. Output datasets (collected in Calibration.xlsx) contain full processors describing farming systems and irrigation areas with both extensive and intensive variables.

Calibration of scaling operations was performed on only two variables. First, the overall production of different crops (total annual tonnes), contrasting model outputs at L1 (the whole region of Almeria) with the annual statistics of the Andalusian administration for the region (Junta de Andalucía, 2013). Second, the total water used by irrigation areas according to management plans was compared against the aggregated net water requirements from the model, divided by a coefficient of irrigation efficiency to obtain gross water use. Comparison for these variables is shown in the following Figs. A1 and A2.

Fig. A1 shows that the model underestimates production of fresh vegetables. This means that either land use or yield data in the model is lower than real values. On the other hand, calculated citrus and olive productions were 20% and 37% larger than statistical estimations for that year, respectively. Regarding water use estimations, the mismatch is especially relevant in DM21, the largest irrigation area with intense greenhouse production (in cluster IA1 in Figs. 5 and 6 of the paper). This means that either total greenhouse land and/or water requirements per hectare for the different crops are larger than reported in data sources, or irrigation efficiency is significantly smaller.

Sequential connections between instances of water bodies and users are not considered in water management plans. Therefore, they were calculated through spatial analyses. Layers of irrigation areas, water bodies and suppliers were overlapped and the most probable water sources for the different users located. This information was contrasted with total withdrawals from those sources for agricultural purposes and adjusted when necessary in order to obtain an estimation of withdrawal by each irrigation area from each aquifer in Almería.

Clustering process

The 16 irrigation areas (L2) in the region were clustered into 7 typologies based on their land use pattern of farming systems (L3).

Table A2
Profiles of irrigation areas based on the land used for different farming systems

Description	Quantitative criteria	Code
Mostly mix of vegetables in greenhouses	>60% of land used for greenhouses, remaining mix of other crops	1
More than half of land used for mix of vegetables in open fields	>50% of land used for open field vegetables mix, remaining citrus or olive groves in intensive production	2
More than half of land used for lettuce production in open fields	>50% of land used for open field lettuces, remaining citrus or olive groves in intensive production	3
More than half of land used for olives production complemented by almonds	>30–50% of land used for olive groves and almonds in intensive production	4
Mostly olives production in hyper intensive production	>30–50% of land used for olive groves in hyper intensive production, 20–40% olive and almond mix, remaining open field or citrus	5
Mostly citrus supplemented by lettuce production in open fields	>40% of land used for citrus production, remaining lettuces in open fields	6
Mix of lettuce, citrus and vegetables in open fields	30% lettuce, 30% citrus, 30% mix vegetables in open fields	7

Table A3
List of indicators used in visualizations.

Indicator	Reference	Unit	Calculation
Water Extraction Index	Fig. 5	%	Divides annual withdrawals from an aquifer by groundwater availability, which is calculated as inflows minus environmental water requirements.
Aquifer withdrawal rate	Fig. 6-1	Hm^3/year	Sum of annual aquifer withdrawal performed by clustered irrigation areas.
Water use pattern	Fig. 6-2	Hm^3/year	Annual water used from different sources by clustered irrigation areas.
Land use pattern	Fig. 6-4	ha/year	Hectares of land used for different crop production by clustered irrigation areas.
Labor	Fig. 6-3	h/ha*year	Hours of labor employed per hectare by farming systems.
Gross Value Added	Fig. 6-3	€/ha*year	Gross added value generated according to price for farmers per hectare by farming systems.
Yields	Fig. 6-3	tonne/ha*year	Yields per hectare by farming systems.

For this purpose, profiles associated with quantitative criteria were defined through a qualitative analysis of most representative patterns (Table A2) and the 16 irrigation areas were coded accordingly (see Ouput/ClusterData.xlsx in the data folder for assignation of irrigation areas to each cluster). Processors variables, including withdrawals from aquifers, were aggregated for the obtained categories and selected indicators calculated as explained in the following section.

Selection of indicators

The following indicators shown in Table A3 were extracted or calculated from the previously described datasets. Structured datasets of indicators can be found in Visualization/VizData.xlsx.

Visualization

The above described indicators were visualized in a canvas with four connected graphs Fig. 6 of the paper), generated using the Python programming language and organized in Tableau. The first graph (F6-1) portrays the rate of annual withdrawal from over-drafted aquifers in Almería, split by clustered irrigation areas. The second graph (F6-2) shows a Voronoi tessellation of the pattern of water resources in the seven clustered irrigation areas in terms of relative annual water supply. The third graph (F6-3) displays three relevant farm production factors in relation to their crop production processes. Finally, the fourth graph (F6-4) shows the Voronoi tessellation of the relative contribution of different crop production processes to the land use pattern of irrigation areas. Altogether, the visualization enables a relational analysis of several causes for the aquifer overexploitation phenomenon, interconnected at different levels in the described nexus network.

References

Agencia Tributaria. 2013. Annual statistics for external trade. Cámara Oficial de Comercio, Industria, Servicios y Navegación de España. Available at (Last access Sep 2018): http://aduanas.camaras.org/.

Albrecht, T.R., Crootof, A., Scott, C.A., 2018. The water-energy-food nexus: a systematic review of methods for nexus assessment. Environ. Res. Lett. 13, 043002. https://doi.org/10.1088/1748-9326/aaa9c6.

Allen, T.F.H., Starr, T.B., 2017. Hierarchy: Perspectives for Ecological Complexity, second ed. The University of Chicago Press, Chicago.

Ahl, V., Allen, T.F.H., 1996. Hierarchy Theory: A Vision, Vocabulary, and Epistemology. Columbia University Press, New York.

Andrews-Speed, P., Bleischwitz, R., Boersma, T., Johnson, C., Kemp, G., vanDeveer, S.D., 2012. The Global Resource Nexus: The Struggles for Land, Energy, Food, Water, and Minerals. Transatlantic Academy, Washington, DC.

Arbib, M.A., Milsum, J.H., Rashevsky, N., Rescigno, A., Richardson, I.W., Roberge, F.A., Rosen, R., 1973. In: Rosen, R. (Ed.). Foundations of Mathematical Biology: Supercellular Systems, III. Academic Press, New York.

Bechtel, W., Richardson, R.C., 2010. Discovering Complexity: Decomposition and Localization as Strategies in Scientific Research. MIT Press.

Bijl, D.L., Bogaart, P.W., Dekker, S.C., van Vuuren, D.P., 2018. Unpacking the nexus: different spatial scales for water, food and energy. Glob. Environ. Change 48, 22–31. https://doi.org/10.1016/j.gloenvcha.2017.11.005.

Cabello, V., Madrid, C.M., 2014. Water use in arid rural systems and the integration of water and agricultural policies in Europe: the case of Andarax river basin. Environ. Dev. Sustain. 16, 957–975. https://doi.org/10.1007/s10668-014-9535-8.

Cai, X., Wallington, K., Shafiee-Jood, M., Marston, L., 2018. Understanding and managing the food-energy-water nexus – opportunities for water resources research. Adv. Water Resour. 111, 259–273. https://doi.org/10.1016/j.advwatres.2017.11.014.

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G.K., Seekell, D.A., Suweis, S., Rulli, M.C., 2018. The global food-energy-water nexus. Rev. Geophys.. https://doi.org/10.1029/2017RG000591.

Fischer-Kowalski, M., 1998. Society's metabolism: the intellectual history of materials flow analysis, part I, 1860–1970. J. Ind. Ecol. 2, 61–78. https://doi.org/10.1162/jiec.1998.2.1.61.

Font Vivanco, D., Wang, R., Deetman, S., Hertwich, E., 2018. Unraveling the nexus: exploring the pathways to combined resource use: unravelling the nexus. J. Ind. Ecol.. https://doi.org/10.1111/jiec.12733.

Franz, M., Schlitz, N., Schumacher, K.P., 2017. Globalization and the water-energy-food nexus – Using the global production networks approach to analyze society-environment relations. Environ. Sci. Policy. https://doi.org/10.1016/j.envsci.2017.12.004.

Galaitsi, S., Veysey, J., Huber-Lee, A., 2018. Where is the added value? A Review of the Water-Energy-Food Nexus Literature. Stockholm Environment Institute, Stockholm SEI working paperAvailable at. https://www.sei.org/publications/added-value-review-water-energy-food-nexus-literature/.

García-García, M.C., Céspedes López, A.J., Pérez Parra y, J.J., Lorenzo Míngue, P. (Eds.), 2016. El sistema de producción hortícola protegido de la provincia de Almería. IFAPA Available at (last access Sep 2018): https://www.researchgate.net/profile/Jeronimo_Perez-Parra/publication/308118507_El_sistema_de_produccion_horticola_de_la_Provincia_de_Almeria/links/57da9cf108ae5292a3767c52/El-sistema-de-produccion-horticola-de-la-Provincia-de-Almeria.pdf.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press.

Georgescu-Roegen, N., 1975. Energy and economic myths: institutional and analytical economic essays. South. Econ. J. XLI (3), 347–381.

Giampietro, M., 2018a. Anticipation in agriculture. In: Poli, R. (Ed.), Handbook of Anticipation. Springer, Cham. https://doi.org/10.1007/978-3-319-31737-3_23-1.

Giampietro, M., 2018b. Perception and representation of the resource nexus at the interface between society and the natural environment. Sustainability 10. article no. 2545 https://doi.org/10.3390/su10072545.

Giampietro, M., Mayumi, K., 2000. Multiple-scale integrated assessments of societal metabolism: integrating biophysical and economic representations across scales. Popul. Environ. 22 (2).

Giampietro, M., Aspinall, R.J., Ramos-Martin, J., Bukkens, S.G.F., 2014. Resource accounting for sustainability assessment: the nexus between energy, food, water and land use. Routledge Explorations in Sustainability and Governance. Routledge, New York.

Gobierno de España. 2015. Segura water district management plan 2015–2021. Available at (last access Sep 2018): https://www.chsegura.es/chs/planificacionydma/planificacion15-21/.

Harwood, S.A., 2018. In search of a (WEF) nexus approach. Environ. Sci. Policy 83, 79–85. https://doi.org/10.1016/j.envsci.2018.01.020.

by Heijungs, R., Suh, S., 2002. The computational structure of life cycle assessment. In: Tukker, A. (Ed.), Eco-Efficiency in Industry and Science Springer Science + Business Media Dordrecht, Dordrecht.

Hernández-Mora, N., Ituarte, L., del, M., La-Roca, F., Calle, A.L., Schmidt, G., 2014. Interbasin water transfers in Spain: interregional conflicts and governance responses. In: Schneier-Madanes, G. (Ed.), Globalized Water. Springer, Netherlands, pp. 175–194.

Howarth, C., Monasterolo, I., 2017. Opportunities for knowledge co-production across the energy-food-water nexus: making interdisciplinary approaches work for better climate decision making. Environ. Sci. Policy 75, 103–110. https://doi.org/10.1016/j.envsci.2017.05.019.

Junta de Andalucía. 2013. Annual agricultural and fisheries statistics. Available at (last access Sep 2018): https://www.juntadeandalucia.es/organismos/agriculturapescaydesarrollorural/consejeria/sobre-consejeria/estadisticas/paginas/agrarias-anuario.html.

Junta de Andalucía. 2015. Andalusian mediterranean basins water district. Management Plan 2015-2021. Available at (last access Sep 2018): https://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.7e1cf46ddf59bb227a9ebe205510e1ca/?vgnextoid=4d01df1837fa1510VgnVCM2000000624e50aRCRD&vgnextchannel=953d4ae7a9aa1510VgnVCM2000000624e50aRCRD.

Kampis, G., 1987a. Some problems of system descriptions I: function. Int. J. Gen. Syst. 13 (2), 143–156. https://doi.org/10.1080/03081078708934964.

Kampis, G., 1987b. Some problems of system descriptions II: information. Int. J. Gen. Syst. 13 (2), 157–171. https://doi.org/10.1080/03081078708934965.

Keairns, D.L., Darton, R.C., Irabien, A., 2016. The energy-water-food nexus. Annu. Rev. Chem. Biomol. Eng. 7, 239–262. https://doi.org/10.1146/annurev-chembioeng-080615-033539.

King, C.W., Carbajales-Dale, M., 2016. Food–energy–water metrics across scales: project to system level. J. Environ. Stud. Sci. 6, 39–49. https://doi.org/10.1007/s13412-016-0390-9.

Louie, A.H., 2009. More Than Life Itself: A Synthetic Continuation in Relational Biology, 1. Ontos Verlag.

Louie, A.H., 2013. The Reflection of Life: Functional Entailment and Imminence in Relational Biology, 2. Springer.

Louie, A.H., 2017. Intangible Life: Functorial Connections in Relational Biology. Cham Springer International.

Martínez Alier, J., Schlüpmann, K., 1987. Ecological economics: energy, environment, and Society. Basil Blackwell, Oxford [Oxfordshire] ; New York, NY, USA.

March, H., Saurí, D., Rico-Amorós, A.M., 2014. The end of scarcity? Water desalination as the new cornucopia for mediterranean Spain. J. Hydrol. 519 (Part C), 2642–2651. Water governance across competing scales: Coupling land and water managementIncorporating water resources in integrated urban and regional planning https://doi.org/10.1016/j.jhydrol.2014.04.023 .

Mayumi, K., Giampietro, M., 2000. Multiple-scale integrated assessment of societal metabolism: introducing the approach. Popul. Environ. 22, 109–153.

Muranetto, S., Witmer, M. 2017. Water-land-energy-food-climate nexus: policies and policy coherence at european European and international scale. SIM4NEXUS Project. Deliverable 2.1. Available at: http://www.pbl.nl/sites/default/files/cms/publicaties/WP2_Deliverable%202.1_15nov17_FINAL.pdf

Nilsson, M., Zamparutti, T., Petersen, J.E., Nykvist, B., Rudberg, P., McGuinn, J., 2012. Understanding policy coherence: analytical framework and examples of sector–environment policy interactions in the EU. Environ. Policy Gov. 22, 395–423. https://doi.org/10.1002/eet.1589.

Pahl-Wostl, C., 2017. Governance of the water-energy-food security nexus: a multi-level coordination challenge. Environ. Sci. Policy. https://doi.org/10.1016/j.envsci.2017.07.017.

Rashevsky, N., 1954. Topology and life: in search of general mathematical principles in biology and sociology. Bull. Math. Biophys. 16, 317–348.

Ripa, M., (Ed). 2017. Report on nexus security using quantitative story-telling. MAGIC project Deliverable 4.1. Available at: http://www.magic-nexus.eu/documents/d41-report-nexus-security-using-quantitative-story-telling.

Rosen, R., 1958. A relational theory of biological systems. Bull. Math. Biophys. 20, 245–260.

Rosen, R., 1970. Structural and Functional Considerations in the Modelling of Biological Organization. The Center.

Rosen, R., 2005. Life Itself: A Comprehensive Inquiry Into the Nature, Origin, and Fabrication of Life. Columbia University Press, New York.

Rosen, R., 2012. Anticipatory Systems: Philosophical, Mathematical, and Methodological Foundations, second ed. Springer-Verlag, New York.

Scanlon, B.R., Ruddell, B.L., Reed, P.M., Hook, R.I., Zheng, C., Tidwell, V.C., Siebert, S., 2017. The food-energy-water nexus: transforming science for society. Water Resour. Res. n/a-n/a https://doi.org/10.1002/2017WR020889.

Shannak, S., Mabrey, D., Vittorio, M., 2018. Moving from theory to practice in the water-energy-food nexus: an evaluation of existing models and frameworks. Water-Energy Nexus. https://doi.org/10.1016/j.wen.2018.04.001.

Söderberg, C., 2016. Complex governance structures and incoherent policies: implementing the EU water framework directive in Sweden. J. Environ. Manage 183 (Part 1), 90–97. https://doi.org/10.1016/j.jenvman.2016.08.040.

Stein, C., Pahl-Wostl, C., Barron, J., 2018. Towards a relational understanding of the water-energy-food nexus: an analysis of embeddedness and governance in the Upper Blue Nile region of Ethiopia. Environ. Sci. Policy. https://doi.org/10.1016/j.envsci.2018.01.018.

Tolon-Becerra, A., Lastra-Bravo, X.B., Fernández-Membrive, V.J., 2013. Huella hídrica y sostenibilidad del uso de los recursos hídricos. Aplicación al Poniente Almeriense. M + A. Revista Electrónic@ de Medio Ambiente 14 (1), 56–86. Available at: https://www.ucm.es/data/cont/media/www/pag-41205/61articulo.pdf (lastly accessed Sep 18).

Valera Martínez, D.L., Belmonte Ureña, L.J., Molina Aiz, F.D., López Martínez, A., 2016. Greenhouse agriculture in Almería. A Comprehensive Techno-Economic Analysis. Cajamar Caja Rural Available at (lastly accessed Sep 18): http://www.publicacionescajamar.es/pdf/series-tematicas/economia/greenhouse-agriculture-in-almeria.pdf .

Venghaus, S., Hake, J.-F., 2018. Nexus thinking in current EU policies – the interdependencies among food, energy and water resources. Environ. Sci. Policy. https://doi.org/10.1016/j.envsci.2017.12.014.

Weitz, N., Strambo, C., Kemp-Benedict, E., Nilsson, M., 2017. Closing the governance gaps in the water-energy-food nexus: insights from integrative governance. Glob. Environ. Change 45, 165–173. https://doi.org/10.1016/j.gloenvcha.2017.06.006.