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Integrated modelling and management of water resources: the ecosystem perspective on the nexus approach

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Addressing challenges of water, energy and food security, nexus approaches towards resources management are being developed and starting to be implemented. However, the ecosystem perspective, essential for sustainable resources management, has been identified as a missing element within earlier nexus assessments. With regard to water they have mainly focused on the allocation to different sectors and users, while ecosystem services were rarely explicitly addressed. Existing aquatic ecosystem models are capable of quantifying a wide range of ecosystem services, but have thus far not been comprehensively used in a nexus context. Recent developments in aquatic ecosystem modelling approaches provide opportunities to achieve the sought integration of ecosystem services in the nexus approach. Therefore, we argue for a stronger role of aquatic ecosystem models in nexus assessments.

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Introduction

In order to address challenges of water, energy and food security, in recent years attention has been paid to truly integrated approaches to resources management across these sectors, and considering interrelated resources in a balanced and coherent way [1,2,3••,4]. The nexus concept (in particular addressing Water, Energy and Food: WEF nexus) is rooted in earlier *integrated* resources management concepts, e.g., Integrated Water Resources Management (IWRM). Considering the need to provide water for people, food, nature, industry and other users [5], IWRM conceptually captures some aspects of the nexus concept [6], but its scope of integration is clearly sectoral [7], thus missing many potential trade-offs as well as synergies. It can be argued that the nexus concept, by making the respective interconnected sectors and resources explicit, offers greater scope for integration than IWRM with its water-centered perspective [8]. Acknowledging challenges in the operationalisation of the nexus approach [9•], it has still proven as a successful communication tool, addressing a wide range of resources, sectors (WEF) and institutions in a balanced manner [10] and its potential to unleash synergies and minimise trade-offs between sectors has been demonstrated [11]. Such a nexus approach, with nexus domains under consideration varying from case to case, is considered to be an essential tool for monitoring progress towards achieving the Sustainable Development Goals (SDGs) [12], which are strongly interrelated [2,3••,13]. Given its wide scope, the nexus concept is particularly suited to addressing resources management across spatial scales and governance levels. For example, downscaled planetary boundaries [14] may support a 'vertical' nexus approach as well as national SDG implementation and operationalisation of resource-related SDGs [10]. The latter certainly include SDG 2 (zero hunger), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), but indirectly all SDGs [11,13].

Given the integrative nature of the nexus approach, it was argued that ecosystem services (ES), including provisioning, regulating and maintenance as well as cultural services (categories following The Common International Classification of Ecosystem Services (CICES), see https://

cices.eu/) have to be considered as central elements in nexus assessments [9•,15•,16]. From a resources perspective, ES are obviously essential for any *integrated* management approach in order to consider all dimensions of sustainability as they provide the basic resource base on which society develops. This holds in particular for the WEF nexus, where the equitable allocation of water resources between these sectors has to integrate knowledge on ES provided by rivers, lakes, wetlands and aquifers, given that the provision of water both in terms of quantity and quality relies on them [17]. Such services include [18]:

Provisioning services:

- Water provision at a distinct quality, depending on its use;
- Biomass production, including fish production (with food and economic implications);

Regulating and maintenance services:

- Self-purification by mineralisation of organic compounds;
- Nutrient retention of N and P (i.e. lowering nutrient loading towards downstream rivers and coasts/estuaries;
- Carbon sequestration;
- Buffering capacity for extreme events (floods and droughts)
- Nutrient recycling, enabling biomass production;

Cultural services:

- Touristic, recreational and religious services, implying sufficient water quantity and quality.

One common concern about earlier integrated resources management approaches was that the ecosystem dimension was neglected (e.g. Ref. [19] with regard to IWRM) and this has similarly been concluded for the nexus [20]. The need for including the ecosystem perspective in the nexus has been emphasised by several studies, but mostly on a rather general and conceptual level [9•,15•,16]. For the WEF nexus, often explicitly termed a security nexus, provisioning services are obviously essential and a matrix framework linking them with life cycle assessment of food production was recently proposed [15•]. As soon as resources (i.e. water) quality gets into focus, regulating as well as cultural services have to be considered. To be able to do this in a systematic way, ES and the respective processes need to be reflected in modelling tools used in nexus assessments (Figure 1). From the (aquatic) ecosystem perspective a large number of modeling tools are available to support management [21], but these models have thus far not been used in nexus assessments.

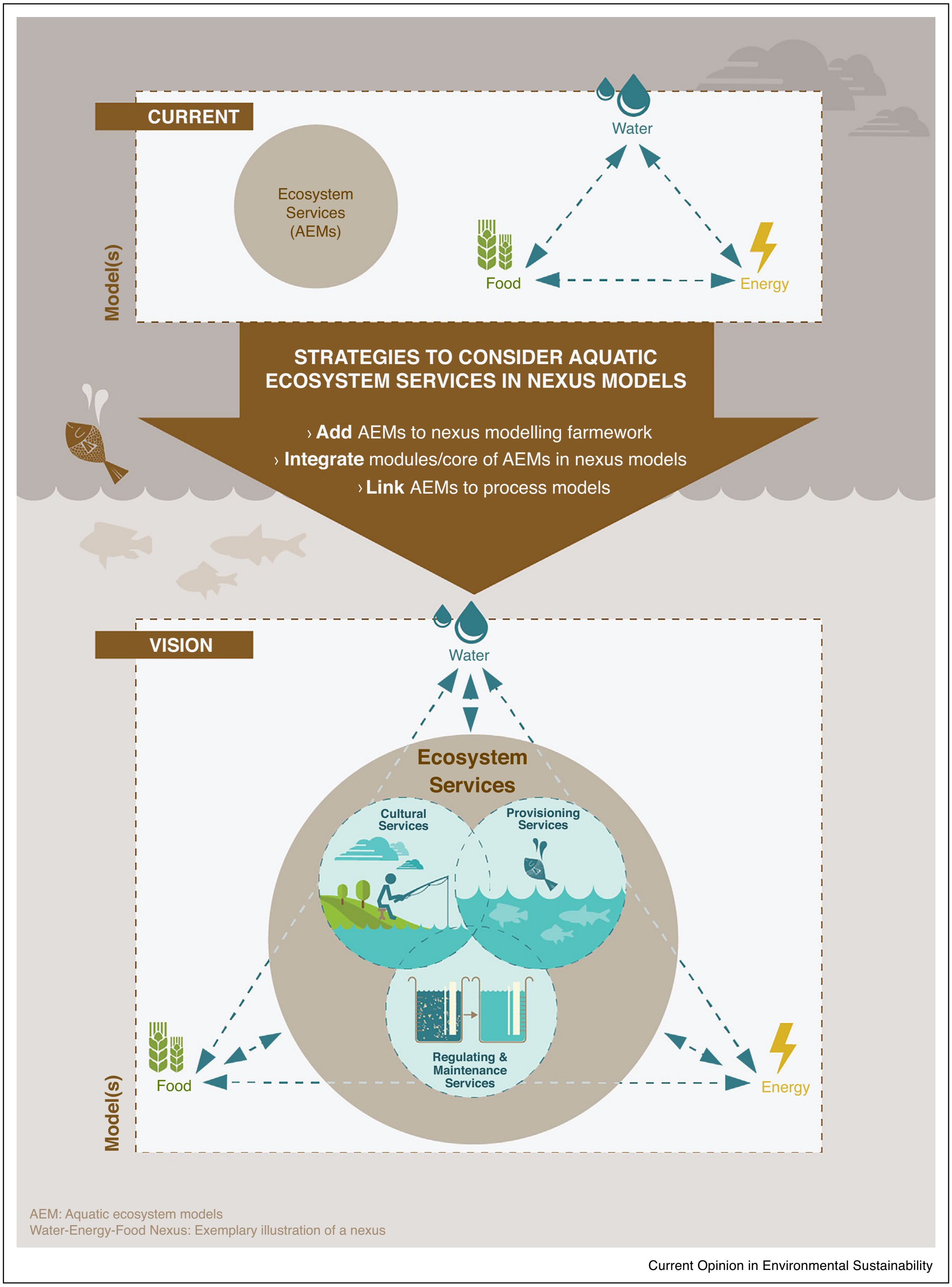
In this paper, therefore, we explore the interrelations between the nexus approach and ecosystem management from both perspectives. Our basic hypothesis is that there is a division between scientific communities focusing on either a nexus approach or on aquatic ecosystem management – linking to and rooted in IWRM. After briefly reflecting on the need for appropriate modelling tools, we take a closer look at current examples of nexus-oriented and ecosystem-based modelling approaches to explore how close or separate both lines of research and the respective communities are. We then provide a perspective on how to close this gap in order to proceed towards modelling tools which better reflect nexus-oriented and sustainable resources management with a focus on water – as related to food and energy security.

Coverage of ecosystem services in current nexus modelling

Several studies point out the need for appropriate nexus tools which would enable the integrative assessment of the considered nexus interlinkages under study [9•,24••,25,26]. Following a systems approach, such tools are essential for understanding complex systems, for scenario analysis and supporting decision making. See, for example, the case of the water–land-use-energy nexus in Mauritius [20] to assess energy and land-use scenarios and their interrelations with water demand and GHG emissions, or the case of the Hehuang region in China, in which the water, power, and environmental systems were analysed using a system dynamics approach [27], further examples are given in Ref. [11]. In general, there is a high and increasing diversity of nexus modelling tools and approaches. These range from specifically designed nexus tools, modelling frameworks combining several tools which individually focus on a specific nexus node (e.g. water, land-use or energy), to individual applications of single models or (loose) combinations of models. While reviewing nexus methods and tools used in previous studies, a number of specifically designed nexus tools were analysed and evaluated [28,29]. All of them, however, were found to have serious limitations in terms of applicability, ease of use and feasibility due to data limitations. Similarly, Albrecht *et al.* [24••] found that most modelling tools used so far in nexus studies actually fail to cover the interlinkages between sectors and resources in a comprehensive way, ES being among those missing elements. With regard to coverage of ES, this was found to be basically restricted to (terrestrial) biomass production in several and water provisioning in some of the evaluated tools. Below we provide a brief review of ongoing nexus initiatives which focus on designing or improving nexus modelling tools, particularly asking how far ES are covered and addressed. Modelling tools extensively discussed in earlier reviews [24••,28,29] will not be considered here.

Several ongoing projects and initiatives are currently active in developing nexus tools, see for instance the nexus cluster (https://www.nexuscluster.eu/). Some of the

Figure 1



Current and envisioned consideration of ecosystem services (ES) in nexus modelling approaches and the link to aquatic ecosystem models (AEMs). Putting ES in the center of the nexus had been proposed before [22,23]; here, we argue that with regard to water-related ES, AEMs, or parts thereof, can be used to achieve this via multiple approaches.

projects explicitly mention ES to be included in new tools which are, however, not available yet. Among the projects included in the nexus cluster, the ongoing EC H2020 project 'Sustainable Integrated Management FOR the NEXUS of water–land–food–energy–climate for a resource-efficient Europe' (SIM4NEXUS, www.sim4nexus.eu) aims at integrated modelling across five nexus domains (water, energy, land, food and climate) and accounting for nexus-relevant policy targets, objectives and measures in 12 case studies ranging in scale from local to global. Key outputs include a comprehensive policy coherence analysis for the 12 cases, nexus trajectories to 2050 based on locally relevant policy objectives, and a suite of serious games [30] – one for each case study. The modelling effort in SIM4NEXUS integrates outputs from a number of 'thematic models' (e.g. energy models, crop models), together with local statistical data and policy analysis for each of the five nexus domains under consideration. While very complex (aquatic) ecosystems and their services are not explicitly modelled within the project, some parameters are implicitly captured in some case studies (e.g. indicators on water quality, nutrient loads from land). However, this was not done in a consistent manner, nor across all the case studies, and neither were ecosystem impacts such as the potential impact to biodiversity accounted for because of the (different) scope of the project.

The initiative on Integrated Solutions for Water, Energy, and Land (ISWEL, see http://www.iiasa.ac.at/web/home/research/iswel/ISWEL.html), used an integrated modelling approach that takes into account multiple global climate change and socio-economic development scenarios. Areas of potential conflict between a range of indicators representing sectoral interests of water, energy and land were identified at global [31] and regional scale [32]. Of the 14 indicators used, seven indicators – to differing degrees – relate to ES, namely: non-renewable groundwater abstraction; drought and peak flow intensities; seasonality; environmental flow exploitation; habitat degradation and nitrogen leaching. As of now, however, options to address ES in these modelling approaches have not been fully exploited. Among those examples provided in Ref. [11] some address provisioning services in terms of agricultural production, but none explicitly covers ES, let alone aquatic ES. Selected land-based ES were also considered in a new tool which focuses on WEF nexus simulations at the local scale [33]. A recent plea to consider 'nature' in the WEF nexus [34] focused on nitrate removal in wetlands as an indicator of water quality regulation but did not consider ES in a more comprehensive way.

The current use of aquatic ecosystem models in nexus context

Aquatic ecosystem models (AEMs) originated from studies on eutrophication and were firstly developed in the 1970s. The major goal of AEMs during that time was to provide quantitative tools for predicting the responses of lakes and reservoirs to nutrient loading, the definition of critical loading levels, and the evaluation of alternative eutrophication control measures [35]. While being kept rather simple initially, many AEMs are nowadays designed as complex system models with respect to their physical representation (1D, 2D, 3D) and the ecosystem architecture including detailed routines for representing trophic interactions, community dynamics, and biogeochemical cycling [36]. Modern AEMs demand detailed input data for meteorological conditions as well as inflow volumes and nutrient loadings from the water bodies' catchment and therefore can be linked to atmospheric or hydrological models. This enables the integration of AEMs into wider model systems at the landscape scale [37•] in order to assess the interaction between land use (including food production), energy production (which links strongly to water demand and quality) climate change, and aquatic ecosystem dynamics. Several examples of AEM integrations into larger scale models were provided recently [37•,38,39]. These examples link catchment models with AEMs and by that establish a model system that consistently simulates water and nutrient fluxes from the catchment into the lake, as well as the corresponding ecosystem and water quality dynamics within the receiving lake. Model results for Lake Beyşehir, the largest freshwater lake in Turkey, suggest that lower nutrient loading will be an option to at least partly offset the negative effects of warming [38], confirming conclusions from earlier studies [40,41]. Interestingly, while Bucak *et al.* [38] and Li *et al.* [39] highlight the integrative nature of their work (and the need for this), they do not put this into the context of the ongoing nexus debate. Similarly, a recent study coupling land-based ecosystem modelling to a hydraulic model (a land–water nexus), did not provide any relation to the current nexus debate [42]. This is another indication that the postulated divide between 'ecosystem modellers' and the 'nexus community' indeed exists.

The way forward

Acknowledging the earlier studies that stress the need to integrate ES in nexus assessments, we found that thus far such integration is only rudimentarily implemented in existing nexus modelling tools. We, therefore, see many opportunities to make use of AEMs in the nexus context using the following approaches (see also Figure 1):

1 Addition of AEMs to a nexus modelling framework to contribute to the incorporation of specific ES;
2 Integrating modules or the core of AEMs – quantifying specific ES – into existing or newly developed nexus models;
3 Linking AEMs to process models addressing, for example, land-use, crop production, soil erosion, water yield and so on in a watershed, to contribute to a

comprehensive analysis of the nexus of water, soil/land, biomass production (food, bioenergy).

We have not been able to find examples of the first approach, but ongoing initiatives to improve AEMs in terms of applicability, user-friendliness, openness, and new implementations in commonly used programming languages such as R (https://www.r-project.org) or facilitating conversions by using a database approach [43] will increase opportunities for such developments and reduce obstacles related to model complexity. Conversely, new nexus tools and modelling frameworks currently under development will also increase the potential for linking with AEMs or core parts thereof. For the second option, there are first examples available as discussed above, as well as ongoing initiatives, for example, the approach in SIM4NEXUS could be adopted and/or extended to include ecosystems by linking the water, agricultural and land sectors to aquatic ecosystem models in order to assess impacts arising from changes in land use patterns in a more explicit and robust manner. Policy targets related to ecosystems and biodiversity could be accounted for in a similar manner, again allowing one to explore the potential impact of such policy decisions on (aquatic) ecosystems using relevant indicators, which themselves can link to SDG goals. Not necessarily requiring the full complexity of AEMs, just considering specific processes or outputs related to specific ES can be sufficient for a well-defined nexus case. The third option also seems promising since some examples mentioned in the section on AEMs already point into this direction, being highly relevant for the WEF nexus, although originally not conceptually framed as nexus projects. This points to a non-technical issue needed to advance the inclusion of ES into the nexus approach: enhanced interaction between the scientific disciplines and communities working on nexus issues or on ecosystem management.

For the integration of AEMs within a wider nexus analysis, a number of requirements need to be met. Obviously, the AEM must produce output that is useful in the scientific and social context and the context must provide the input necessary for the nexus model. Such output will depend on the specific nexus study and will have to be defined for each case. Potential examples related to water and food provisioning include nutrient loads, biodiversity indicators, and carbon sequestration. In the case of non-sectoral specific nexus modelling approaches such as system dynamics modelling, the output could be of any metric and in many formats, allowing for flexibility on the side of the AEM and easy integration into the wider nexus model. The main downside of this approach is that relationships between the AEM output and the other nexus parameters (e.g. energy demand, food production) need to be defined. Moreover, the AEM stands a good chance of being operated outside the range of conditions for which it was developed. This calls for a process-based AEM that is rooted in first principles such as the conservation of mass and trophic efficiency, rather than a data-driven statistical approach. Then, the AEM must capture potential non-linearities in ecosystem responses to anthropogenic stress. In particular regimes shifts in aquatic ecosystems from a plant to a phytoplankton dominated state may have large consequences of the capacity of segments of a hydrological network to retain nutrients [44]. AEMs will also require more and well-defined interfaces with management practices, for example, reservoir operation, remediation actions or nutrient management in order to reflect their cross-sectoral effects. Through this, AEMs will also capture the interactions between water quantity management and ES. Recently, it was proposed that anthropogenic stress on ecosystems will most likely induce adaptive responses in ecosystems through plasticity, species sorting or micro-evolution and if so, AEMs will need to cover these as well [45].

Process-based AEMs that capture some or all of those dynamics vary widely in complexity at which they cover the ecological processes involved. Obviously, the AEM of choice should match the complexity of the nexus context, in which it is integrated to get a balanced result in terms of processes that are covered, data flows between components and run time performance of the integrated model. A number of developments related to AEMs indicate that their integration into nexus assessments is becoming increasingly feasible, including closer integration of hydrodynamics, strengthening the interaction between water quantity and quality dynamics [46], the possibility of using multiple software frameworks concurrently [47] and performing ensemble modelling [48].

The increasing diversity of nexus modeling tools should be embraced as an opportunity rather than a disadvantage, as concluded earlier for AEMs [21]. From this point of view, we do not advocate aiming for consensus among tool developers towards a perfectly unifying modelling tool [29], since every nexus problem is different, calling for the use of multiple approaches [24••]. Identifying the most appropriate (set of) tools could be facilitated by specific platforms enabling a detailed comparison of existing tools [49], and should be decided upon for each individual case study, accounting for the specific requirements (based on processes to be analysed) and the appropriate level of complexity [50].

While we refrain from claiming that ES have to be considered in all nexus assessments, we are convinced that, given the strong role of the nexus approach for the 2030 agenda, ES have to be given more attention and visibility in the nexus. This holds in particular for the development of transition pathways and scenarios towards achieving SDGs including those emphasising supply by resource sectors, SDG 2 (zero hunger), SDG 6 (clean water and sanitation) and SDG 7 (affordable and clean energy), but also those emphasising the preservaton of earth systems, SDG 13 (climate action), SDG 14 (life below water) and SDG 15 (life on land). This highlights the urgent need to have ES represented in models. When focusing on water resources management, we envision a strong future role for AEMs to include ES in the nexus approach. The required bridging between respective scientific communities would be one step towards the interdisciplinarity needed to achieve integrative nexus tools as proposed by Albrecht *et al.* [24••]. Ultimately, nexus assessments might draw from model libraries within environmental observatories [51] to predict systems resilience and the role of ES therein.

Conflicts of interest statement

Nothing declared.

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