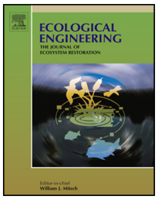
Ecological Engineering 108 (2017) 489–497

Contents lists available at ScienceDirect

Ecological Engineering

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



Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management

Josefin Thorslund[a,*], Jerker Jarsjö[a], Fernando Jaramillo[a,b], James W. Jawitz[c], Stefano Manzoni[a], Nandita B. Basu[d], Sergey R. Chalov[e], Matthew J. Cohen[f], Irena F. Creed[g], Romain Goldenberg[a], Anna Hylin[a], Zahra Kalantari[a], Antonis D. Koussis[h], Steve W. Lyon[a], Katerina Mazi[h], Johanna Mård[i], Klas Persson[a], Jan Pietroń[a], Carmen Prieto[a], Andrew Quin[a], Kimberly Van Meter[d], Georgia Destouni[a,j]

[a] *Department of Physical Geography and the Bolin Centre for Climate Research, Stockholm University, SE-106 91, Stockholm, Sweden*
[b] *Stockholm Resilience Center, Stockholm University, Kräftriket 2B, Stockholm, Sweden*
[c] *Soil and Water Science Department, University of Florida, Gainesville, FL, 32611, United States*
[d] *Civil and Environmental Engineering and Earth and Environmental Sciences, University of Waterloo, Waterloo, N2L 3G1, Canada*
[e] *Faculty of Geography, Lomonosov Moscow State University, 119991, Moscow, Russia*
[f] *School of Forest Resources and Conservation, University of Florida, Gainesville, FL, 32611, United States*
[g] *Department of Biology, Western University, N6A 5B7, London, ON, Canada*
[h] *Institute for Environmental Research and Sustainable Development, National Observatory of Athens, GR-152 36, Palea Penteli, Athens, Greece*
[i] *Department of Earth Sciences, Uppsala University, 752 36, Uppsala, Sweden*
[j] *Navarino Environmental Observatory (NEO), Stockholm University, Messinia, GR-240 01, Kalamata, Greece*

ARTICLE INFO

Article history:
Received 8 May 2017
Received in revised form 3 July 2017
Accepted 7 July 2017
Available online 18 July 2017

Keywords:
Wetland ecosystems
Flow-path
Ecosystem services
Large-scale
Change driver
Ecological engineering

ABSTRACT

Wetlands are often considered as nature-based solutions that can provide a multitude of services of great social, economic and environmental value to humankind. Changes in land-use, water-use and climate can all impact wetland functions and services. These changes occur at scales extending well beyond the local scale of an individual wetland. However, in practical applications, engineering and management decisions usually focus on individual wetland projects and local site conditions. Here, we systematically investigate if and to what extent research has addressed the large-scale dynamics of landscape systems with multiple wetlands, hereafter referred to as wetlandscapes, which are likely to be relevant for understanding impacts of regional to global change. Although knowledge in many cases is still limited, evidence suggests that the aggregated effects of multiple wetlands in the landscape can differ considerably from the functions observed at individual wetland scales. This applies to provisioning of ecosystem services such as coastal protection, biodiversity support, groundwater level and soil moisture regulation, flood regulation and contaminant retention. We show that parallel and circular flow-paths, through which wetlands are interconnected in the landscape, may largely control such scale-function differences. We suggest ways forward for addressing the mismatch between the scales at which changes take place and the scale at which observations and implementation are currently made. These suggestions can help bridge gaps between researchers and engineers, which is critical for improving wetland function-effect predictability and management.

1. Introduction

Nature-based solutions (NBS) is a newly coined umbrella concept (Albert et al., 2017). It relates to the use of nature for addressing a range of global environmental and social challenges, such as climate change and pollution of water systems (Cohen-Shacham et al., 2016). NBS are determined by the natural functions of ecosystems, which for example includes natural attenuation processes that frequently involve microbial removal of contaminants from groundwater (Scow and Hicks, 2005). Quantitative understanding of the contributions of natural systems towards reaching various targets (e.g. related to water quality) is a prerequisite for scientists,

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* Corresponding author.
E-mail address: josefin.thorslund@natgeo.su.se (J. Thorslund).

http://dx.doi.org/10.1016/j.ecoleng.2017.07.012

managers and policymakers. This is to be able to clarify potential needs for additional technical or ecological engineering solutions (e.g. enhancing contaminant removal) required to reach set targets (e.g. Nesshöver et al., 2017; Mitsch, 2012).

Wetlands are known for their provisioning of ecosystem services and thus have great potential to be used as nature-based solutions to address a variety of environmental, social and economic challenges. Common multi-beneficial ecosystem services from wetlands include carbon sequestration (e.g. Mitsch et al., 2013; Bridgham et al., 2006), water quality protection (e.g. Verhoeven et al., 2006; Mitsch et al., 2001), coastal protection (e.g. Temmerman et al., 2013; Gedan et al., 2011), groundwater level and soil moisture regulation (e.g. Hefting et al., 2004; Xiong et al., 2003), flood regulation (e.g. de Groot et al., 2002; Acreman and Holden, 2013) and biodiversity support (e.g. Gibbs, 2000; Dudgeon et al., 2006). However, despite their potential, there has been a continued and rapid decline in wetland areas globally. Although the absolute number of global wetland loss (both in number and area) are uncertain, and some regions of the world, such as the US and Europe, have slowed down the rate of wetland loss substantially over the last decades, many regions are still experiencing rapid wetland loss (Mitsch and Gosselink, 2015; Davidson, 2014). Nevertheless, the global value of wetland ecosystem services ($26.4 trillion/yr) is still estimated to contribute more than 20% of the total value of ecosystem services globally, exceeding the contributions of terrestrial forests and coral reefs (Costanza et al., 2014). This highlights the need for evaluating how to best use wetlands as cost-efficient and sustainable nature-based solutions to a range of current and future challenges.

Climate change and large-scale land-use changes (Seneviratne et al., 2006), as well as changes in water use and demographic pressures (Destouni et al., 2013), affect large-scale water fluxes and balances. These changes should therefore also be expected to affect wetland functions and associated ecosystem services. Particularly, understanding impacts of regional-global change on wetland functions and associated ecosystem services, and evaluating suitable management practices and engineering solutions for mitigating them, is a major challenge for scientists, engineers and stakeholders. To address this challenge, and support management and engineering solutions, we need to first have a good understanding of how natural wetland systems interact with their surroundings at various scales and how this can be evaluated.

A fundamental question that arises in the face of the issues outlined above is: what are the relevant scales to study wetland functions? We will here argue for the need to consider the large-scale functioning of the hydrologically coupled system of multiple wetlands and their total hydrological catchment, hereafter referred to as a wetlandscape (see Fig. 1 and further motivated in Section 2). More specifically, we investigate to which extent large-scale wetlandscape functions, services and impacts may differ from those of individual wetlands. Also, can they even be predictable from the behavior of individual wetlands? If not, what are collective results of evaluations about expected large-scale change impacts on the functioning of whole wetlandscapes? These questions have not, to the best of our knowledge, previously been systematically investigated.

2. Problem statement

A call for conducting wetland research at the landscape scale was made almost 30 years ago when Preston and Bedford (1988) stated that "*the scale must be enlarged from the individual wetland project to include the broader landscape. Only this broader view can provide the context within which decision-makers can evaluate the potential cumulative effects of individual mitigation decisions on broad-scale patterns of wetland diversity*". While it is clear that studies on individual wetlands have been crucial for enhancing our understanding of fundamental wetland functions (e.g. Perry et al., 2004; Drexler and Bedford, 2002), evidence is now mounting that critical ecosystem services indeed emerge from the aggregated effects of individual wetland interacting with their surrounding landscape (e.g. Cohen et al., 2016).

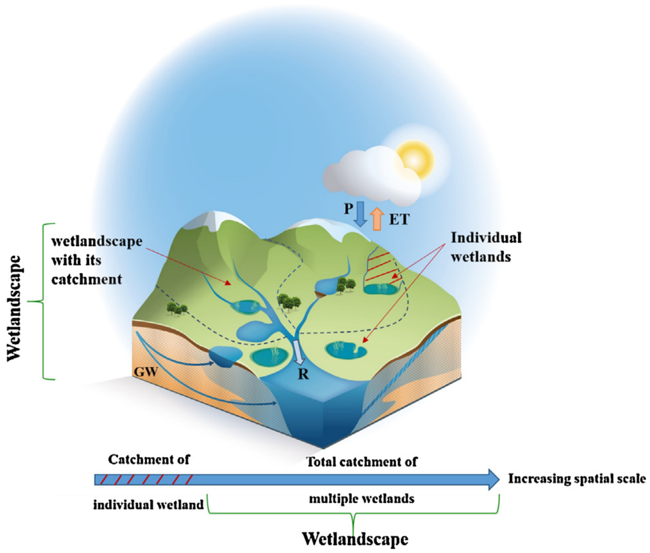


Fig. 1. Conceptual sketch of a wetlandscape. A wetlandscape consists of multiple wetlands that are hydrologically connected within an associated larger hydrological catchment than that of an individual wetland. The associated large-scale water fluxes precipitation (P), evapotranspiration (ET), runoff (R) and groundwater (GW) flows are represented by arrows in the landscape. A wetlandscape and its associated total catchment is not a static unit but will be defined at and represent various spatial scales (exemplified by dashed lines).

Even today though, mitigation decisions are typically made at the level of individual wetland projects, and engineering solutions as well as management and policy decisions are often based on understanding isolated parts of the water system, such as treating groundwater and surface water as separate components (Destouni et al., 2015; Borer et al., 2014). This fragmented approach could lead to the risk of implementing costly solutions that may be inefficient due to overlooking many dynamic effects that emerge at larger scales of wetlandscapes. This may adversely affect wetland management and global wetland loss.

We see two main reasons why the consideration of wetlandscapes may substantially improve wetland science, management and policy efforts. The first is process-oriented and relates to the inherent water flux interactions between wetlands and the hydrological system. This includes groundwater and evapotranspiration exchanges (McLaughlin and Cohen, 2013), which are naturally limited by the borders of entire interconnected hydrological catchments (Destouni et al., 2015). Additionally, large-scale water balances in a landscape can change considerably as a result of cross-scale changes in climate, land-use and water-use, with emerging patterns at integrated scales of whole drainage basins (Jaramillo and Destouni, 2015, 2014). By definition, such large-scale water-balance dynamics and changes will, in a basin with multiple connected wetlands, influence and interact with the whole wetlandscape.

The second reason is model-dependent and relates to the constraints of climate and Earth System models that are used to assess future climate change and its impacts. These models all have spatial resolutions that are clearly coarser than the size of most individual wetlands. Thus, predictions regarding specific wetlands will most likely be highly uncertain, whereas regional predictions have much more potential to be accurate (Bring et al., 2015). This makes it neither possible nor advantageous to refine the resolution of such global models down to each individual wetland part of a larger wetlandscape. It is therefore important to consider appropriate model and measurement levels for large-scale and long-term representations of whole wetlandscape dynamics and changes (Luo et al., 2011). The scales needed for quantifying functions of, and impacts on, wetlandscapes will vary from case to case, but will probably encompass scales at least in the order of square kilometers. There are also many examples of wetlandscapes extending well beyond 10,000 km^2 (Table A2). Given the overall inconsistency between local management practices, expected wetlandscape dynamics and large-scale model tools, it is critical to systematically evaluate how well research knowledge translates to these larger interconnected scales that are needed for bridging the gaps between research and engineers working on addressing challenges of regional-global change.

3. Material and methods

To evaluate the open research questions stated in the introduction, we here perform a *meta*-analysis that includes: (i) a synthesis of functional differences between individual wetlands and wetlandscapes (Section 3.1); (ii) an expert survey on wetlandscapes and their changes (3.2); and (iii) a general wetland literature survey (3.4). We also perform a hydro-climatic change analysis across all of the investigated wetlandscape study-sites (3.3).

3.1. Synthesis of functional differences between individual wetlands and wetlandscapes

Results regarding potential differences between the function and interactions of individual wetlands and large-scale wetlandscapes were synthesized from on-going and published research across 21 investigated study-sites (Fig. 2). Key methods used for deriving basin-scale hydrological flows, flow-path distributions and retention functions of wetlands and wetlandscapes among these study-sites include distributed runoff quantifications using the PCRaster-based Polflow type of models (de Wit, 2001), analytical model development (Törnqvist et al., 2015; Quin et al., 2015), as well as field-measured (Chalov et al., 2016) and synthesized data on discharge and contaminant concentrations (Törnqvist et al., 2015; Quin et al., 2015; Thorslund et al., 2012).

Contaminant transport and transformation along various hydrological transport-pathways in the Selenga delta wetlandscape (site 9) was estimated. Specifically, runoff quantifications were combined with synthesized measurement data of contaminant concentrations, to enable estimates of contaminant mass flow distributions in the wetlandscape and relating this to the difference between inflowing and outflowing mass through wetlands (reflecting attenuation-retention in individual wetlands; Chalov et al., 2016). In the Amu Darya wetlandscape (site 13), an analytical model was developed, which considered changes in nutrient attenuation as a function of extent of re-circulation of water through the larger wetlandscape (due to extensive irrigation). The model results were compared with measurement data to assess the contribution of the individual wetlands, as well as the whole wetlandscape, to observed downstream reduction in nutrient loads (Törnqvist et al., 2015). In two Swedish wetlandscapes (sites 5–6), the nutrient retention of individual wetlands was compared to that at landscape-scale through analytical modelling based on statistical analysis of wetland frequency and catchment inputs-outputs of nutrients for multiple sub-catchments across the investigated wetlandscapes (Quin et al., 2015). For more detailed methods and model descriptions for all of these sites, see e.g. Chalov et al. (2016), Törnqvist et al. (2015), Quin et al. (2015) and Thorslund et al. (2012).

3.2. Expert survey on wetlandscapes and their changes

To assess the collective knowledge on impacts of large-scale changes in wetlandscapes, the 21 focus wetlandscape sites from active research projects were systematically surveyed. This was done in connection with a designated workshop in Greece (April 30th–May 1st, 2015), involving the authors of this paper; a group of eco-hydrological researchers, working within a global wetland network (http://www.gwennetwork.se/). Our author group have on-going research projects (involving various topics and research groups) on wetlandscapes that include and represent a range of wetland types, hydroclimatic conditions, large-scale change drivers and their impacts, and site locations across Arctic, Europe, Asia, Africa, North and South America regions (Fig. 2). Specifically, we developed an expert judgement protocol, where each site-responsible researcher has, for their respective wetlandscape site and research group, been requested to grade the experienced (enhanced, impaired, unknown) impacts of pre-selected global change drivers on a set of pre-selected large-scale wetland functions. The water-related drivers of global change on which we focused our assessment include; *wetland drainage, irrigation expansion, waterborne urban or industrial pollution, engineered flow regulation*, and *hydroclimatic change*. These drivers are expected to affect different wetlandscape functions, of which we have here focused on investigating the following water-related ones: *biodiversity support, nutrient and pollutant retention, coastal protection, groundwater and soil moisture regulation,* and *flood regulation*.

This survey thus brings together experiences from both published and on-going research from each research group that is working actively with hydrological quantifications on each of these 21 study-sites. A more detailed summary of site conditions, such as wetland types, climate and land-uses can be found in Tables A.1 and A.2 in the Appendix, including also key publications where more information about the sites and applied research methods are described.

3.3. Hydro-climatic change analysis

In order to perform a consistent analysis of a common set of hydro-climatic parameters across all of the investigated wetlandscape study sites, a first-order hydro-climatic assessment was performed. We analyzed historic trends in some relatively readily obtainable (from available open data) global change drivers. More specifically, we compiled large scale, long-term data on temperature (T) and precipitation (P), from which we have further calculated evapotranspiration (ET) and related runoff (R; estimated as P-ET) over the period 1901–2014, and quantified the changes in these variables from 1901 to 1957 to 1958–2014. The compilation was based on gridded data of monthly precipitation and temperature from the Climate Reseach Unit (CRU) dataset CRU TS 3.10 (Harris et al., 2014). See results in Fig. 2b–i and Appendix A2 for information on data processing and calculations.

3.4. General wetland literature survey

Lastly, we conducted a comprehensive general survey of the published scientific literature (a total of 20,997 published papers), on the considered wetland functions and change drivers. This was done particularly to investigate the relative frequency of small-scale versus large-scale studies, and to see how this literature compares to the expert judgments surveyed for the specific investigated wetlandscape sites in Fig. 2. We used the Web of Science^{TM} Core Collection (WoS) and directed the search to include

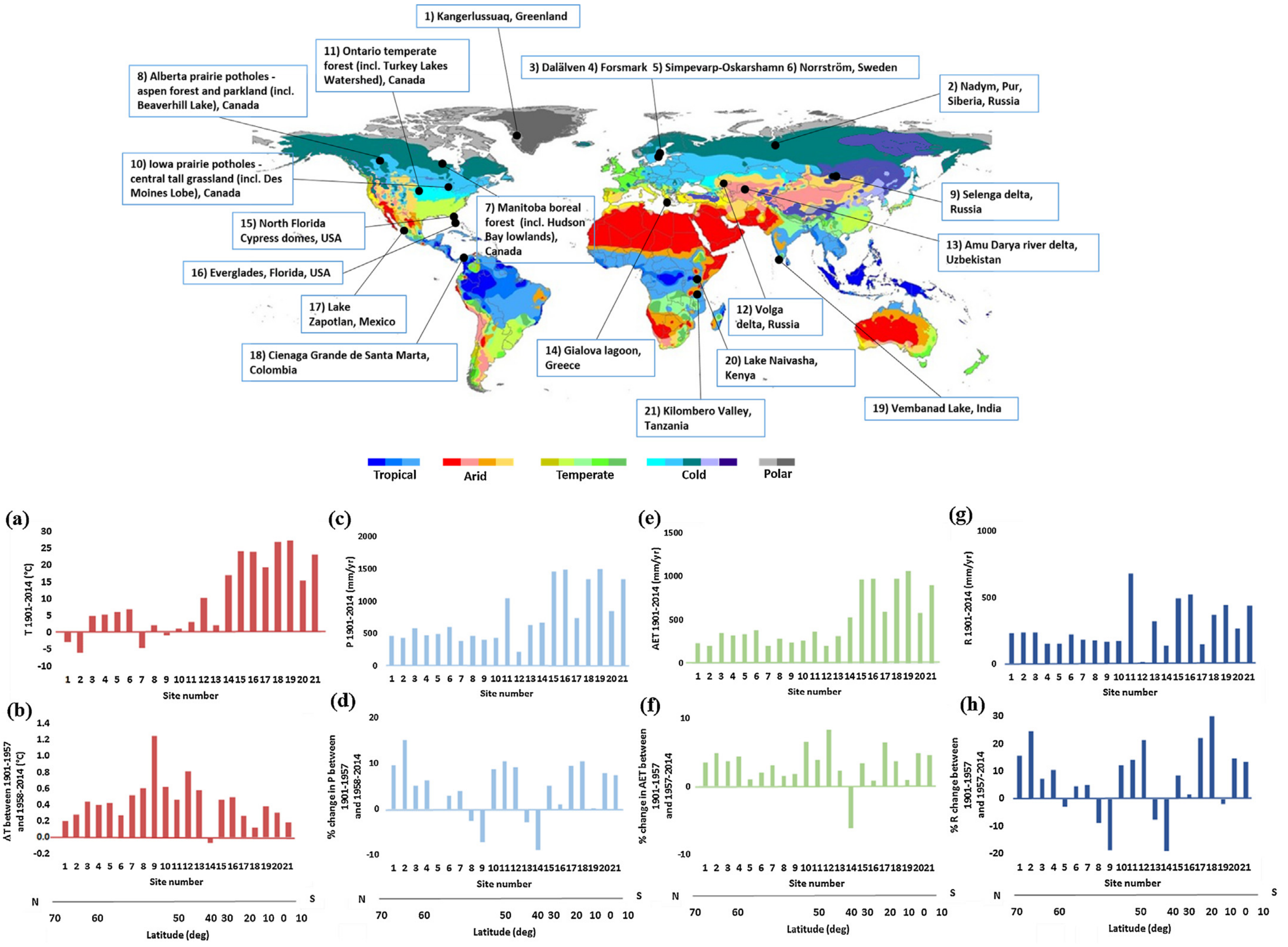


Fig. 2. The locations of the twenty-one investigated in-depth research wetlandscape sites (a) and long-term average (1901–2014) hydroclimatic conditions (b, d, f, h) and data-implied changes between 1901 and 1957 and 1958–2014 (c, e, g, i). The locations are shown on a background map of the Köppen-Geiger climate classification system, as updated by Peel et al. (2007) and numbered according to Latitudinal position. Temperature (T, in °C) and precipitation (P, in mm/yr) information are obtained directly from available data for a circle with an area of 1000 km^2, defined around the mid-coordinate of each wetlandscape sites, while actual evapotranspiration (AET, in mm/yr) and runoff (R, in mm/yr) are first-order estimates for the same spatial extent based on the T and P data for AET and as P-ET for R. Further documentation about the sites, data sources and methods can be found in Appendix.

all wetland-related publications, published up until the search date (May 3rd, 2017) (see general survey results in Fig. 5b Appendix A3 and Table A3 for further methods and detailed results).

4. Results and discussion

4.1. *Differences between individual wetlands and wetlandscapes: converging evidence on flow-path relevance*

Whether or not wetlands contribute to landscape-scale functions may, to a large degree, depend on natural flow-path conditions across the landscape and the degree of interactions of individual wetlands with surface and groundwater pathways (Fig. 3). The results regarding flow-paths and wetland functions at local wetland compared to large-scales integrated wetlandscapes at several of the investigated sites, show contrasting patterns. Firstly, research at the two different coastal wetlandscapes in Sweden (Fig. 2; site 5–6) showed that, although local wetlands have high capacity of retaining nutrients, their large-scale coastal protection function was undetectable for water entering the Baltic Sea (Quin et al., 2015). Specifically, the developed analytical model approach indicated that the reason for this result was that only a small fraction of flow-paths through the landscape intersect with these wetlands, whereas the majority of polluted flows did not (illustrated in Fig. 3A). Thus, the landscape-scale contribution of investigated wetlands to coastal protection was not achieved, rather other landscape characteristics, such as flow-path length, were identified as more important (Quin et al., 2015).

Secondly, measurements within the Selenga delta (Fig. 2; site 9) showed efficient metal removal capacity (77–99% reductions in loads) of individual wetlands. However, similarly as the coastal protection function of the Swedish wetlandscapes, our mass flow quantifications showed that most of the flow did not pass through these wetlands. Measurements across the larger wetlandscape indicated that only a maximum of 30 % (in some parts as low as 5–10 %) of the total flow passed through small channels with extensive wetland areas. Thus, the main parts of the total flows and associated loads passed through larger channels of the different delta sectors, resulting in contaminated sediment plumes reaching the recipient (Chalov et al., 2016 and illustrated in Fig. 3).

In addition to baseline flow-path distributions and interactions with wetlands across a wetlandscape, many landscapes are also extensively and increasingly modified by human activities. This may considerably change ambient conditions and introduce new

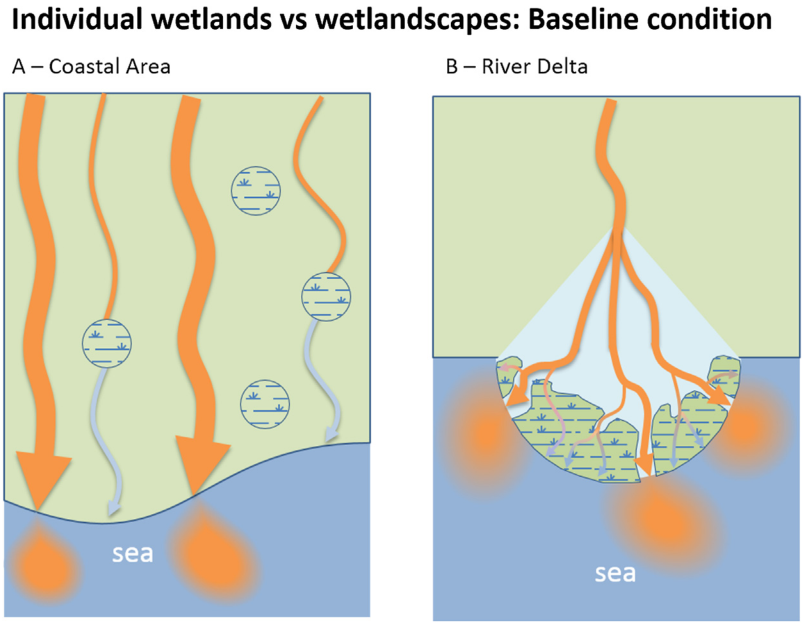


Fig. 3. Conceptual illustration of two wetlandscapes under baseline conditions; a coastal area (A) and a river delta (B), both of which discharge into the sea. Natural flow-pathways are shown as arrows, whose width indicates flow magnitude and color indicates water quality (orange more polluted, blue less polluted). Individual wetlands may considerably alter the water quality along the flow pathways that intersect those wetlands. However, at the scale of wetlandscapes, a certain fraction of flow pathways may pass between the wetlands. It is an open question to which degree the total flow through a landscape needs to be connected to the wetlands of the wetlandscape, in order to effectuate a particular service (e.g., good water quality of the sea). It is also an open question how existing knowledge of local wetland services and landscape characteristics relates to services of wetlandscapes. This issue is likely to be relevant in all natural landscapes, as well as in those affected by human interventions, although in the latter case, other factors may additionally come into play (see Fig. 4). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

coupled wetland-human-landscape dynamics (Fig. 4). For instance, our results from the highly managed Amu Darya wetlandscape site in Central Asia, which includes a vast river delta near the former shoreline of the Aral Sea (Fig. 2, site 13), shows that circular flow-paths across the wetlandscape resulted in decreasing nutrient loads downstream, although nutrient inputs to the system has increased with agricultural expansion. Due to water re-circulation, characterized by considerable return flows from the irrigated fields of the wetlandscape (Fig. 4), the sum of water diversions along the river has become as much as six times greater than the discharge of the river itself (Törnqvist et al., 2015). Despite considerable problems near the agricultural plots, related to persistently increasing fertilizer use since the 1950′s and soil salinization, the concentrations and loads of nitrogen in the downstream part of the Amu Darya delta have decreased by factors between three and six. Törnqvist et al. (2015) showed that the only plausible explanation for this behavior was the increasing water re-circulation.

Whereas effects of re-circulation have previously been investigated at the laboratory and plot scales (e.g. Hitomi et al., 2006; Feng et al., 2004), systematic investigations at the scale of wetlandscapes are yet lacking, beyond the here mentioned example. Notably, there is observational evidence from other regions regarding decreasing nutrient loads under agricultural intensification (e.g., Brown et al., 2011; García-Garizábal and Causapé, 2010). However, since the underlying mechanisms have not been scrutinized, regional to global effects of changed water re-circulation (and more generally, changes in flow-pathways within wetlandscapes) are largely unknown. It is plausible that such effects would also influence the cycling of other substances such as phosphorous, metals and organic matter, which would have important implications for the provision of ecosystem services. Furthermore, at least in arid and semi-arid regions, on-going climate change is likely to alter flow-paths in wetlandscapes in a way that increases the water recirculation (all other conditions being equal), which could imply associated recipient load reductions of nutrients at larger scales (Jarsjö et al., 2017).

All of these detailed investigated site examples highlight feedbacks between multiple wetlands and their surroundings and the emerging process complexity at the scales of wetlandscapes. These detailed case studies support the hypothesis that the aggregated interactions of wetlands with the larger landscape and its changes can only be realized and monitored at the scale of wetlandscapes.

4.2. What is known about large-scale functions of and impacts on wetlandscapes?

Our synthesis of the 21 wetlandscapes shows that many large-scale driver-function impacts are still unknown (white circles, Fig. 5a), even though the emerging impact relevance is high for several of the considered change drivers (darker blue color, Fig. 5a). Drainage is the only driver that emerges as relatively well-known, regarding impacts on multiple wetlandscape functions (Fig. 5a). For this driver, there is consensus on large-scale function impairment for the majority of the studied sites and functions (Fig. 5a). This result is similarly reflected in the share of general publications addressing large wetlandscape scales (Fig. 5b, dark blue bars). The share, compared to local-scale studies (Fig. 5b, light blue bars) is higher for drainage (26%) than for other investigated change drivers (Fig. 5b). This may suggest that impacts of drainage are comparatively well explored and understood at these larger scales. The reasons for this emerging understanding may be the traditional landscape-scale execution of drainage measures, which usually involves multiple wetlands across the landscape and associated studies that have considered impacts on larger scales and for multiple wetlands (e.g. McCauley et al., 2015). One clear example of large-scale impacts of wetland drainage is that of the former Great Black Swamp in Ohio, USA. Draining of this wetlandscape (>10,000 km^2) for agricultural purposes have caused severe nutrient loadings to enter the Lake Erie, which is now hyper-eutrophic,

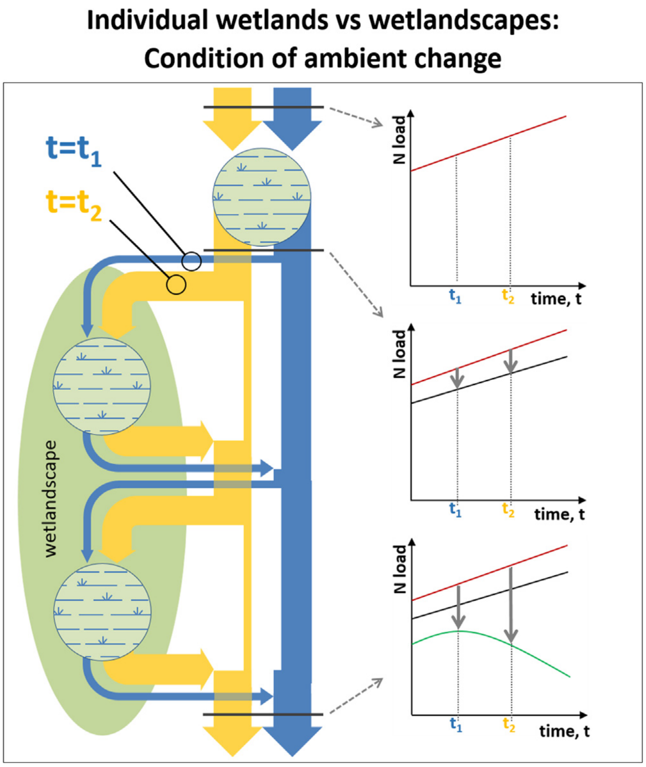


Fig. 4. Conceptual illustration of a wetlandscape with human modified flow-pathways, due to diversion of water from a river. Such diversions can for instance be the result of agricultural intensification with increased re-routing of river water (between t = t1 and t = t2) to irrigated agricultural fields. Agricultural intensification is commonly also associated with increased fertilizer use and nutrient loading at the agricultural plots (top graph, panel a). An individual wetland can alleviate downstream impacts of increased fertilizer application. Nevertheless, output loads will also increase with time (middle graph, panel b) unless it is compensated by exceptional improvements in wetland removal efficiency, which is rarely the case. However, at the scale of wetlandscapes, increased water diversions are likely to result in increased total flow-path length as well as increased water circulation through the wetlandscape (yellow flow-path). This provides favorable conditions for increased nutrient removal efficiencies of the wetlandscape (bottom graph, panel c). Note that the illustrated changes in flow-paths occur outside of the individual wetland units, which means that the overall dynamics emerge through interactions between the changing landscape and the wetlands. Such dynamic effects of wetlandscapes are likely to co-exist with baseline flow-path effects shown in Fig. 3.

with associated severe environmental, economic and social consequences (Levy, 2017; Stewart, 2015).

Beyond the well-quantified impacts of large-scale drainage, impacts of the other considered global change drivers emerge as largely unknown (Fig. 5). Of all the considered global change drivers (Fig. 5a, columns), hydroclimatic change emerges as the key global-change driver, with impacts that are considered relevant (55 ± 18%) for most of the investigated wetlandscape functions. Yet, this driver is also associated with the overall largest research gaps across the investigated sites (Fig. 2). Comparing our collective knowledge with the general wetland literature, we see that, although investigations of hydroclimatic change at individual wetland scale are numerous in absolute numbers (Fig. 5b, light blue bars and Appendix: Table A3), the low proportion of large-scale studies (23%; Fig. 5b, dark blue bars) may indicate that impacts on wetlandscapes are also generally underexplored. Such underexplored questions at wetlandscapes may include how hydroclimatic change affects water balances (Jung et al., 2010), hydrologic flows and flow-pathways (Holden, 2005), water temperature (Sjöberg et al., 2016), permafrost thaw (Schuur et al., 2015), release, retention and loading of waterborne substances (Jarsjö et al., 2017; Lyon et al., 2010), wetland occurrence within wetlandscapes (Karlsson et al., 2015) and the consequences of all such water-related changes on the large-scale wetlandscape functions and services.

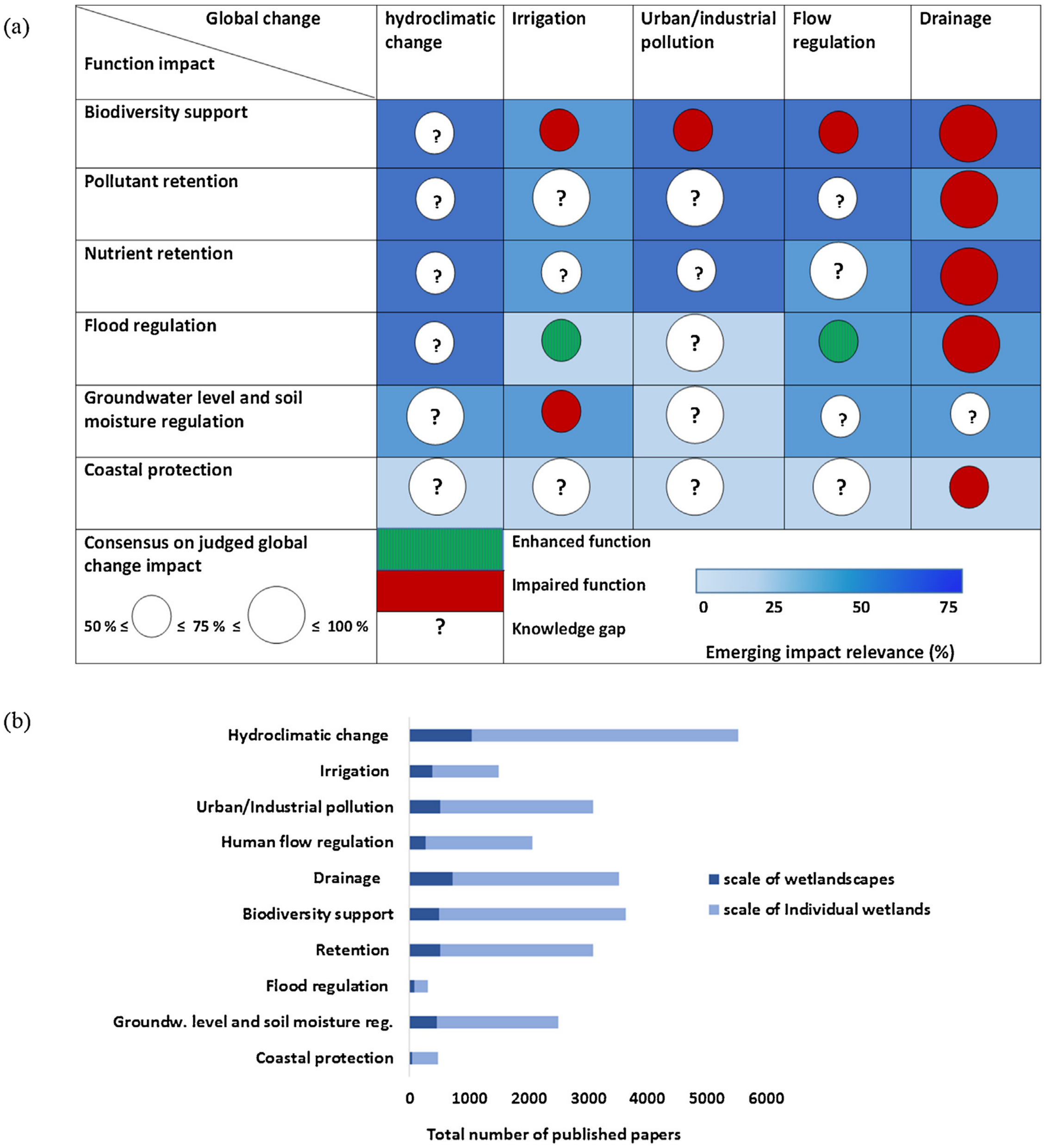
The conducted hydroclimatic change analysis results (Fig. 2b–i) across the study-sites show that large-scale hydroclimatic changes have indeed already occurred at most of the sites over the last century, with regard to both surface temperature (Fig. 2c) and water fluxes (Fig. 2e, g, i), with intensification of the latter in most wetlandscapes (simultaneous increase in P, R and ET). The largest temperature changes have occurred at the relatively cold, northern boreal and temperate sites with mean annual temperature less than around 10 °C (sites 1–13). The greatest hydrologic changes from 1901 to 1957 to 1958–2014 occur for annual average runoff (Fig. 2), which has increased at most of the investigated wetlandscapes. For sites where changes so far have been relatively small, climate change projections indicate greater future changes (Sarukhán and Whyte, 2005). In addition to atmospheric climate change, changes within the landscape itself, for example human developments of irrigation expansion/intensification and engineered flow regulation (Jaramillo and Destouni, 2015), can also drive hydroclimatic changes in large-scale water fluxes (Jaramillo and Destouni, 2014). Taken together, although the hydroclimatic change analysis shows large-scale changes in water fluxes occurring across most investigated wetlandscapes, it is clear from our site expert survey that the basics of how these changes impact various wetlandscape functions remains largely unknown and needs further attention.

For the function of large-scale coastal protection, paradoxical results emerge from the expert survey (Fig. 5a), with impacts on this function being judged as largely unknown (77 ± 24%) but also as of relatively low relevance (17 ± 4%) for the specific investigated wetlandscapes (Fig. 2). This collective relevance judgment emerges, even though many of the investigated wetlandscapes are part of coastal catchments (76%). An explanation may be that this coastal dimension has so far had low priority in funded research projects. A consistent relevance result is also reflected in the general literature survey by a comparatively small fraction of wetland-related publications (11%) addressing the coastal protection function at large scales (Fig. 5b and Table A.3). However, in contrast to these relevance-judgment indications, high-profile publications have stated a high relevance of wetlands for protecting coastal areas and a need for large-scale restoration of wetlands for this purpose (e.g. Temmerman et al., 2013).

For the large-scale wetlandscape functions of nutrient and pollutant retention, our site survey (Fig. 5a) indicates a perception of considerably higher research relevance (49 ± 15%) than for the coastal protection function. Yet, also for these retention functions knowledge gaps emerge for the large-scale impacts of most change-drivers (60 ± 20%). Similar indications of under-exploration at wetlandscape relevant scales also arise from the general literature survey, with research attention having mostly focused on individual wetlands (80% of published papers, Fig. 5b, light blue bars) rather than on the large-scale function of whole wetlandscapes. These survey and literature results highlight that for several key-valued wetland functions and impacts, dynamics at the scale of entire wetlandscapes are largely unknown and, as shown in Section 4.2, may potentially differ from dynamics of individual wetlands at more local scales.

5. Concluding remarks and ways forward for research, engineering and management

Our systematic assessment of both in-depth research experience and the wetland literature has shown that many challenges remain in extending our understanding of wetlandscapes. There is a clear gap between traditional research expertise from local wetland projects and its translation to larger scales. This gap hinders



(a)

Global change / Function impact	hydroclimatic change	Irrigation	Urban/industrial pollution	Flow regulation	Drainage
Biodiversity support	?	🟥	🟥	🟥	🟥
Pollutant retention	?	?	?	?	🟥
Nutrient retention	?	?	?	?	🟥
Flood regulation	?	🟩	?	🟩	🟥
Groundwater level and soil moisture regulation	?	🟥	?	?	?
Coastal protection	?	?	?	?	🟥

Consensus on judged global change impact
50 % ≤ ○ ≤ 75 % ≤ ○ ≤ 100 %

🟩 Enhanced function
🟥 Impaired function
? Knowledge gap

Fig. 5. (a) Expert-judged impacts of water-related global change drivers on investigated wetlandscape functions and their research relevance, based on active research by the authors across the investigated global wetlandscapes (Fig. 2). (b) Summary of results from the general literature survey, showing the number of published articles considering only individual wetlands (light blue) and those considering larger-scale wetlandscapes (dark blue); for more details about this survey, see Appendix A3 and Table A3. In panel (a), the color of the circles shows the most frequently judged impact on each function (green – enhanced, red – impaired, white – knowledge gap) from each global change driver. The size of the circles shows the collective consensus level for the impact: large circles indicate consistency in more than 75% of the judgments regarding the impacts on each function, whereas small circles indicate 50–75% consensus. The background color shows the emerging impact relevance of each global change driver-impact combination across the investigated sites, calculated as the actual number of answers relative to the maximum possible number of answers for each driver-impact combination. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the development of practical management, engineering and policy solutions that are needed to limit further global wetland deterioration and associated loss in valuable ecosystem services. Overall, the mismatch between the scales at which hydrological changes take place and the scale at which observations and predictions are made has to be resolved in order to increase our understanding on how hydroclimatic and landscape-driven changes impact wetlandscape functioning. Such efforts should address both upstream and downstream conditions along the land-coast interface. For example, systematic hydrological and hydrochemical monitoring downstream of whole wetlandscapes will capture aggregated wetlandscape responses to various large-scale change-drivers, which may be critical for the ability to test hypotheses regarding such responses to global change. Since our results show emerging new functions and functional differences at the scale of wetlandscapes, strategic efforts need to consider both parallel and circular flow-paths, through which wetlands are interconnected in the larger landscape.

Specific ways to investigate wetlandscapes will vary, depending on region and objectives, but will likely require a combination of ground-based measurements (e.g. parallel hydrogeochemical monitoring in both groundwater and surface water components of the landscape), analytical modelling and statistical approaches (Törnqvist et al., 2015; Quin et al., 2015) as well as remote sensing techniques, which are synthesized and interpreted using GIS based approaches (e.g. Settele and Wiemers, 2015; Queiroz et al., 2015). There is also potential for using conservative solutes for exploring large-scale hydrological interactions and changes between wetlands and the larger landscape (Abbott et al., 2016). Additionally, new modeling and assessment frameworks exist that may be particularly useful for coastal wetlandscapes (e.g. Mazi et al., 2013; Mazi et al. 2016; Koussis et al., 2012) and should now be applied and evaluated at cross-regional scales. More than 40 million people live in coastal cities today (Temmerman et al., 2013) and coastal areas are subject to especially high climate- and human-driven change pressures (Ferguson and Gleeson, 2012). Extended efforts on investigating the large-scale coastal protection function of wetlands should be a key priority, since impacts here were not well understood according to our synthesis (Fig. 5a), only few studies exist at large scales (Fig. 5b) and coastal areas rarely have appropriate large-scale monitoring (Giosan et al., 2014).

Overall, without understanding of both natural and changing ambient conditions on the larger scales of whole wetlandscapes, we risk missing critical linkages, which may lead to contradictory interpretations and inefficient and costly restorations of wetlands in non-optimal locations in the landscape (Palmer et al., 2014). Understanding how contrasting functions of wetlands depend on scale and aggregated interactions with the larger landscape needs to be accounted for by ecological engineering approaches (Mitsch and Gosselink 2000). If not, there is a risk for adverse effects on mitigation capacity, sustainability and cost-efficiency of chosen management solutions. Our assessment highlights where efforts of cross-disciplinary research on large-scale functions of whole wetlandscapes, and their potential changes, are urgently needed. Targeting these efforts will be a critical first-step for bridging gaps between research and engineering, which could significantly improve our capacity for using wetlands as large-scale nature-based solutions.

Acknowledgements

This research was supported by The Swedish Research Council Formas (Project No. 2012-790) and the Navarino Environmental Observatory (NEO). The Russian partners were funded from the Russian Scientific Foundation (project No. 14-17-00155). Publication was assisted by U.S. National Science Foundation (grant number 1619948) supporting EcoSummit 2016 Sustainability: Engineering Change. The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2017.07.012.

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