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Title:

Aquatic carbon-nutrient dynamics as emergent properties of hydrological, biogeochemical and ecological interactions: scientific advances

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Key points

- Fine-scale water, carbon, and nutrient hydro-biogeochemical interactions can result in ecosystem level emergent properties
- A multi-scale, interdisciplinary approach and the “best” data available are required for improved understanding and management
- Contributions to this special issue highlight paths toward advancing the science and management of water, carbon, and nutrient interactions

Abstract

Carbon and nutrient dynamics in aquatic systems often emerge as the result of hydrological, biogeochemical, and ecological interactions. Due to the multi-scale and multi-disciplinary nature of these process interactions, research into aquatic carbon and nutrient dynamics is becoming increasingly interdisciplinary. The motivation for this special issue came from an international workshop titled “Hydro-Biogeochemical Processes: Mechanisms, Coupling, and Impact”, which took place from October 27 to October 31, 2015 at China University of Geosciences, Wuhan, China. During this workshop, scientists from various countries and disciplines met to discuss current work and future advances on topics such as: the hydro-biogeochemistry of Earth’s critical zone, stream-groundwater interaction zones, aquatic ecosystem processes, and dynamics at land-atmosphere, land-ocean, and human-natural interfaces. Contributions to this special issue on “Emergent aquatic carbon-nutrient dynamics as products of hydrological biogeochemical and ecological interactions” include papers from authors who attended the workshop, and from those who responded to the open solicitation for papers. Our aim in organizing this special issue
is to stimulate continued discussion and collaboration across disciplinary boundaries in order to
further our collective understanding of aquatic carbon-nutrient dynamics.

Keywords: aquatic ecosystems, emergent properties, hydrology, biogeochemistry, ecology,
nutrients, carbon, hydro-biogeochemical interactions

1. Introduction

Carbon and nutrient dynamics affect the fundamental structure and function of aquatic
ecosystems, including rivers, estuaries, lakes and wetlands. These dynamics emerge from
complex interactions among hydrological, biogeochemical and ecological processes. For
example, factors such as hydrologic flow paths and residence times often play key roles in the
rates, magnitude, and spatial extents or locations of aquatic carbon and nutrient (e.g., nitrogen,
phosphorous, sulfur) processing. These factors, together with other interconnected processes
(e.g., human activities, aquatic ecological dynamics), lead to organized biogeochemical patterns -
in space and time - across various aquatic systems.

In human-dominated watersheds, carbon and nutrient dynamics are modified by elevated
nutrient delivery to surface waters, which in turn, affects aquatic ecosystem health. In
agricultural watersheds, nutrients may accumulate in the upper soil horizons during dry periods
after fertilization and nitrogen fixation, leading to rapid flushing to deeper soil horizons and into
rivers via macropore or tile drainage networks during subsequent rainfall events (e.g., Bechtold
et al. 2003, Li et al. 2010). Correspondingly, urban watersheds are hydrologically “flashy” due to
increased imperviousness, reduced surface roughness and channelized streams. These conditions
lead to rapid pulses of nutrients to streams and limited opportunity for in-stream nutrient
processing and removal (e.g., Beaulieu et al. 2015). In both instances, excess nutrients react with organic carbon in the fluvial network, potentially causing aquatic ecosystem degradation, including acidification of streams and lakes (Driscoll et al. 2003), over-enrichment of estuaries and, consequently, eutrophication (Diaz and Rosenberg 2008) and hypoxia (Rabalais et al. 2002). Human activities can, therefore, fundamentally change aquatic ecosystem composition and function (as can natural disturbances, e.g. loss of canopy cover) that affect carbon and nutrient dynamics.

It is clear that multiple interacting processes across a range of spatiotemporal scales influence carbon and nutrient dynamics and therefore functions of aquatic ecosystems. However, a coherent understanding synthesized across physical and biological disciplines to interpret and predict the complex and often non-linear ecobiogeochemical behavior of aquatic systems, and improve potential watershed management, is currently lacking. In this special issue on “Emergent aquatic carbon-nutrient dynamics as products of hydrological biogeochemical and ecological interactions” we highlight novel research findings, future research needs and potential paths toward improved understanding of carbon and nutrient dynamics that are the result of hydrological, biogeochemical, and ecological interactions, as well as other factors such as water management.

2. Special issue on emergent aquatic carbon-nutrient dynamics

The motivation for this special issue came from an international workshop titled “Hydro-Biogeochemical Processes: Mechanisms, Coupling, and Impact”, which took place from October 27 to October 31, 2015, at China University of Geosciences, Wuhan, China. During this workshop, scientists from various countries and disciplines met to discuss current research,
challenges, and future research directions in ecosystem hydro-biogeochemistry. Research topics included the hydro-biogeochemistry of Earth’s critical zone, the permeable layer from the tops of trees to the bottom of the groundwater. Research examined stream-groundwater interactions and dynamics at land-atmosphere, land-ocean, and human-natural interfaces. This special issue thematically builds upon the presentations and initial discussions that occurred during the international workshop. With this special issue, we hope to stimulate further discussion and interdisciplinary collaboration on these topics and synthesize emergent themes from the papers published herein (Figure 1).

2.1. Small-scale processes as drivers of large-scale patterns

Hydrological, biogeochemical, and ecological patterns observed at the stream reach (100s of m²), to landscape (100s of km²) or larger extents often demonstrate emergent properties wherein large-scale patterns arise from smaller scale processes (Cheng and Basu 2017, Li et al. 2017, Roche et al. 2017). Furthermore, characteristics of a system expressed at a broad spatial or temporal scale are not necessarily evident at finer spatial scales (Corning 2002).

In this special issue, Li et al. (2017) highlight how fine-scale (<25 cm) patterns of hyporheic flow and microbially mediated denitrification can affect nitrogen removal rates at the stream reach (100s of meters) and larger spatial scales. Azizian et al. (2017) demonstrate how nitrogen processing in stream hyporheic zones can also be influenced by the spatiotemporal structure of groundwater flow, whereby higher rates of vertical groundwater flux generally diminish stream nitrogen processing. Accordingly, turbulence-driven hyporheic flow dynamics at the sub-meter scale, and groundwater flow at the riffle-pool sequence scale, represent nested processes that simultaneously modulate stream nitrogen processing (Azizian et al. 2017, Li et al. 2017).
While landscape level hydro-biogeochemical patterns can be driven by physical (Azizian et al. 2017) and microbial (Roche et al. 2017) processes occurring at sub-centimeter scales, measuring, understanding, and modeling these fine-scale processes present extensive challenges. Azizian et al. (2017) detail one observational challenge: although sub-centimeter processes have importance to stream denitrification rates, measuring, or at least adequately representing, process heterogeneity at sub-centimeter scales remains a challenge. Roche et al. (2017) describe a second challenge: identifying how small-scale biofilm structure controls fine particle retention at the stream reach scale. Because it is impossible to measure the full extent of fine-scale heterogeneity of processes and characteristics in streams and watersheds, scientists are required to determine the acceptable spatial granularity of measurements based on the scientific objective or management target.

Complementary to observations, modeling approaches can assist in understanding how small-scale processes emerge as larger scale patterns, and provide insight beyond observational data alone. For example, fine-scale heterogeneity not captured by observations can be represented using probabilistic models (Azizian et al. 2017). From these integrated measurement and modeling approaches applied at fine scales, a new, more “complete” set of information is derived that can then be linked to empirical or process-based models at larger scales to facilitate scaling sub-meter processes to landscape biogeochemical patterns. While this procedure may seem theoretically clear, coupling processes and patterns across scales in realistic, predictive models remains a challenge for interdisciplinary studies of aquatic ecosystems from hydrological, biogeochemical, and ecological perspectives.

2.2. Process understanding at multiple spatial scales
The papers in the special issue evaluate processes across multiple spatial scales and highlight complex interactions among hydrological, biogeochemical, and microbial processes that influence aquatic carbon and nutrient dynamics. Roche et al. (2017) describe the physical structure of benthic biofilms at fine spatial scales (µm), which can control fine particle retention but not deposition rates. The authors describe how biofilm-mediated retention of fine particulate organic matter affects stream organic carbon cycling and watershed carbon export. However, these fine-scale processes are often not considered in models that quantify or simulate hydrological transport and biogeochemical processes at large spatial scales (e.g., at the reach or watershed scale (Roche et al. 2017)).

Ye et al. (2017) demonstrate that larger rivers may be more important for nutrient processing than previously recognized. This is in contrast to previous work that underscored the importance of small streams in regulating fluvial nitrogen dynamics at river network to continental scales (Alexander et al. 2000, Peterson et al. 2001, Gomez-Velez et al. 2015). The importance of larger rivers in nitrogen removal processes has been traditionally underappreciated due, in part, to the lack of field data on nitrogen processing in large river systems (Ensign and Doyle 2006). In fact, most field studies, and data generated from them, have been limited to a relatively narrow range of spatial measurements (Roche et al. 2017) and have typically excluded fine-scale (µm) and larger river measurements (Ye et al. 2017).

This special issue further highlights emergent carbon and nitrogen processes at catchment (Kasurinen et al. 2016), river network (Ye et al. 2017), national (Destouni et al. 2017), and global-scales (Cheng and Basu 2017). Kasurinen et al. (2016), for example, show that multiple mechanisms, including soil temperature, catchment water storage, and land-cover can influence landscape level dissolved organic carbon (DOC) dynamics in boreal catchments in Sweden.
Additionally, the timing of DOC release from soils varied between forest-dominated and mire-dominated catchments (Kasurinen et al. 2016). Specifically, in forest-dominated catchments, DOC release was greatest when soil temperature was low, while the opposite was true in mire-dominated catchments. This highlights the need to capture process heterogeneity in field data and modeling in order to properly represent variability in mechanisms of DOC export among catchments.

Ye et al. (2017) highlight variability in the dominant mechanisms controlling retention of various solutes (e.g., nitrate, ammonium, and phosphorous) within a single river network. For example, ammonium uptake was not significantly correlated with any environmental variables, but nitrate uptake was associated with chlorophyll a concentration and land-use. Soluble reactive phosphorous uptake was linked with agricultural land-use and suspended sediment concentration, likely reflecting phosphorus-sediment sorption dynamics (Ye et al. 2017). The lack of relationships between ammonium uptake and various environmental characteristics might be a consequence of biological preference for ammonium relative to nitrate. Thus, biological processing can mask land-cover and land-use impacts particularly when the nutrient of concern is in high demand.

Cheng and Basu (2017) synthesized data from 600 lentic systems (lakes, reservoirs, and wetlands) around the globe and found that nutrient (total nitrogen, total phosphorus, nitrate, and phosphate) removal rate constants in these systems were inversely proportional to water residence time. The inverse relationship between reaction rate constants and residence time was related to lentic system morphometry and volume to surface area relations. In smaller lentic systems with shorter residence times, more of the water and solutes are in contact with sediment boundaries, thus promoting higher processing rates. Further, upscaling empirical data revealed
the importance of small wetlands in nutrient removal processes. Specifically, 50% of the
landscape-scale nitrogen removal occurred in wetlands smaller than 350 m$^2$, underscoring the
important role of small wetlands in nutrient processing across the landscape (Cheng and Basu
2017).

2.3. Linking science and management

A goal of many projects across the basic to applied science continuum is using scientific
understanding to guide real-world action (Stokes 1997). While the importance of this broader
impact is increasingly emphasized, linking science and management remains a challenge. This is
particularly true, as Destouni et al. (2017) emphasize, because data are often limited to conduct
complete assessments on the effectiveness of management approaches to improve water quality.
For instance, in Sweden monitoring data necessary to evaluate ecosystem status is available for
only 1% of the stream and lake water bodies classified under the EU Water Framework Directive
(WFD) (Destouni et al. 2017). Accordingly, there is a need for multi-scale experimental and
monitoring data, incorporated into a multi-disciplinary framework, to improve understanding and
upscaling capabilities and to determine how finer-scale processes result in larger-scale patterns.

Multiple other challenges for linking science with management objectives exist, some of
which are highlighted in this special issue. For example, although small wetlands may play a
disproportionately large role in nutrient retention (Cheng and Basu 2017), wetland area-function
relationships are not yet fully integrated into mitigation strategies. Approaches that incorporate
the nutrient retention and water quality improvement potential of small wetlands, lakes, and
reservoirs can help enhance mitigation strategies. Additionally, nutrient water quality assessment
frameworks that evaluate loads, as opposed to concentrations, may not be able to assess human-
driven impacts on inland water quality (Destouni et al. 2017). As such, use of concentration data may be more appropriate to reveal human-driven water quality impairment and nutrient impacts on coastal receiving bodies. In addition to determining the “best” data to evaluate water quality impacts, these monitoring data need to be of adequate resolution in both space and time. Even in developed countries such as Sweden, data availability limits these types of assessments (Destouni et al. 2017), and these data limitations are even greater in developing countries (Riveros - Iregui et al. 2018).

3. Summary and outlook

The majority of the papers in this special issue highlight the need for a multi-scale, interdisciplinary measurement and modeling approach, which would assist in improved aquatic resource management. For example, the multi-scale approach will allow for μm-cm scale processes to be evaluated at larger scales (1-100m) where ecobiogeochemical patterns are typically observed. Further, research that involves measuring and modeling emergent carbon and nutrient dynamics, as well as other biogeochemical processes, needs to cross scientific disciplines in order to be useful in supporting management objectives. For example, Li et al. (2017) recommend “increased synergy of hydrological, biogeochemical, and microbiological field investigations”. A multi-disciplinary and multi-scale framework on ecobiogeochemical processes and patterns will likely deepen our understanding of aquatic ecosystems, and should generate new data to both inform and improve larger scale models, and guide aquatic resource management. Future research should aim to incorporate this multi-faceted approach, as all of these components will be necessary to develop a coherent understanding to interpret and predict the complex and often non-linear ecobiogeochemical behavior of aquatic systems.
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Figure captions

Figure 1. Conceptual illustration of central concepts from the special issue. Many of the papers note that meso- and large-scale patterns can emerge from fine-scale processes (emergent properties). However, observing fine-scale heterogeneity and upscaling that information remains a challenge. As such, there is a need for multi-scale approaches to understanding eco-hydrobiogeochemical dynamics. Additionally, while this understanding is likely to improve management, there is currently a lack of data required to assess the effectiveness of water quality management. Providing effective management at the large-scale will require the “best” data and the ability to expand fine-scale process understanding to meso- and large-scale extents.

References


Rabalais, N. N., R. E. Turner, and D. Scavia. 2002. Beyond Science into Policy: Gulf of Mexico Hypoxia and the Mississippi River Nutrient policy development for the Mississippi River watershed reflects the accumulated scientific evidence that the increase in nitrogen loading is the primary factor in the worsening of hypoxia in the northern Gulf of Mexico. *Bioscience* **52**:129-142.


Figure 1.
Emergent and multi-scale nutrient, C, and H₂O processes: central concepts

**Concept 1:** Multi-scale, interdisciplinary approaches are needed to improve science and management.

**Concept 2:** Effective management requires scientific understanding and the “best” data available for assessment.

**Concept 3:** Fine-scale processes and their heterogeneity cannot be fully measured - mixed observation and modeling approaches are required.

**Concept 4:** Large-scale patterns are often the scale of observation - they can emerge from fine-scale process.

**Concept 5:** Providing information useful at the large-scale requires fine-scale understanding and careful upscaling.