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Sediment carbon fate in phreatic karst (Part 1): Conceptual model development

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ABSTRACT

Recent research has paid increased attention to quantifying the fate of carbon pools within fluvial networks, but few, if any, studies consider the fate of sediment organic carbon in fluviokarst systems despite that karst landscapes cover 12% of the earth's land surface. The authors develop a conceptual model of sediment carbon fate in karst terrain with specific emphasis upon phreatic karst conduits, i.e., those located below the groundwater table that have the potential to trap surface-derived sediment and turnover carbon. To assist with their conceptual model development, the authors study a phreatic system and apply a mixture of methods traditional and novel to karst studies, including electrical resistivity imaging, well drilling, instantaneous velocimetry, dye tracing, stage recording, discrete and continuous sediment and water quality sampling, and elemental and stable carbon isotope fingerprinting.

Results show that the sediment transport carrying capacity of the phreatic karst water is orders of magnitude less than surface streams during storm-activated periods promoting deposition of fine sediments in the phreatic karst. However, the sediment transport carrying capacity is sustained long after the hydrologic event has ended leading to sediment resuspension and prolonged transport. The surficial fine grained laminae occurs in the subsurface karst system; but unlike surface streams, the light-limited conditions of the subsurface karst promotes constant heterotrophy leading to carbon turnover. The coupling of the hydrological processes leads to a conceptual model that frames phreatic karst as a biologically active conveyor of sediment carbon that recharges degraded organic carbon back to surface streams. For example, fluvial sediment is estimated to lose 30% of its organic carbon by mass during a one year temporary residence within the phreatic karst. It is recommended that scientists consider karst pathways when attempting to estimate organic matter stocks and carbon transformation in fluvial networks.

1. Introduction

Fluvial networks are recognized to not only act as conveyors of sediment organic carbon to the ocean, but also to serve as ecosystems that can actively turnover carbon (Battin et al., 2008). Sediment carbon enters the fluvial system via multiple routes which include overland runoff, subsurface flow, mass wasting, and abscission as well as from autochthonous growth within the fluvial system (Ford and Fox, 2014; Hotchkiss and Hall, 2015). It is now recognized that sediment carbon is an important energy source for decomposers and that microbial oxidation results in the production of carbon dioxide and increasingly degraded terrestrially-derived carbon longitudinally in a fluvial system (Swift et al., 1979; Moore et al., 2004). However, the degradation state of sediment carbon and its downstream fate remain highly uncertain with open questions regarding the spatial variability of turnover, temporary burial, and removal of sediment carbon from active carbon cycles (Cole et al., 2007). In this context, one area that has not been well investigated is sediment carbon fate in fluvial systems that drain karst landscapes.

Karst landscapes are typified as solutionally dissolved landscapes that are dominated by secondary and tertiary porosity features (e.g., macropores, fractures, and conduits) that produce low-resistance pathways for water transport (Thrailkill, 1974; Smart and Hobbs, 1986; Pronk et al., 2009b). When coupled to surface streams of the fluvial network, mature karst topography is well-recognized to include subterranean fluid pathways that act as turbulent conduits conveying fluid from surface sinks termed swallets to sources called springs (White, 2002). Karst watersheds often

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carry high loads of sediment brought in by sinking streams and other karst features (Drysdale et al., 2001). In this manner, karst topography provides subsurface pathways for water, sediment, and carbon transport whereby both terrestrially- and aquatically-derived sediment carbon can be temporarily sequestered and transformed only to resurface further downstream. It is highly reasonable that temporarily stored sediment carbon is oxidized and results in a net production of CO_2 given that bacteria and other microbes within epilithic biofilms in subsurface karst utilize particulate and dissolved organic carbon as an energy source (Chapelle, 2001; Danovaro et al., 2001; Simon et al., 2003, 2007; Goldscheider et al., 2006; Humphreys, 2006). Accounting for the spatiotemporal distribution and variability of organic matter inputs, turnover, and fluxes has been identified as one of the greatest challenges in estimating sediment carbon fate in karst (Simon et al., 2007; Pronk et al., 2009a). Thus, the motivation of this paper is towards elucidating the role of hydrologic processes impacting sediment carbon in fluviokarst landscapes and working towards a conceptual model of sediment carbon fate within fluviokarst systems.

A precursor to a conceptual model of sediment carbon impacted by karst is the non-trivial task of estimating the morphology of karst systems, hydraulics of karst water conveyance, and physics of subsurface sediment transport within karst conduits. The comprehensive review of karst hydrology by White (2002) suggested that sediment transport in karst settings remained one of the most unstudied aspects of karst in need of research. Since that time, a number of groups have investigated the ability of fluviokarst networks to transport sediment and have found that rainfall activated surface tributaries can carry high sediment loads and provide quickflow to the subterranean karst (Hart and Schurger, 2005; Massei et al., 2003); karst drainages entrain and transport sediment loads as function of fluid intensity, similarly to surface streams (Dogwiler and Wicks, 2004); and karst systems store and convey a distribution of sediment under varying ground saturation, moisture, and discharge conditions (Hart and Schurger, 2005; Herman et al., 2008). From recent sediment transport studies, an important feature has been the realization of a sub-classification of karst in phreatic systems. Phreatic conduits are situated below the water table and therefore have a downstream hydraulic control structure, i.e., subterranean dam, or adverse conduit gradient in the streamwise direction that produces saturated flow conditions. In terms of hydraulics, phreatic conduits have an upper limit for their energy gradient and thus upper limit for fluid conveyance due to the existence of the downstream controls. The fluid energy threshold of the phreatic conduits offers the potential to trap sediment either temporarily or permanently (Herman et al., 2008), which highlights the potential for sediment carbon mineralization within the fluviokarst system.

Advancement in our understanding of sediment carbon fate and hydrological processes in karst relies on the application of new or advanced instrumentation within karst systems as well as adopting existing methods from other fluvial settings and applying them to karst. Methods in karst have been greatly advanced in recent years, with a number of methods available for hydrologic analysis. Water conveyance methods generally consist of gaging stations for flow estimation installed at swallow holes and springs (Mahler and Lynch, 1999; Bonacci, 2001; Reed et al., 2010), piezometers for continuous measurement of the groundwater table (Long and Derickson, 1999), and natural as well as artificial tracers for understanding water origin and connectivity between surface and subsurface pathways (Katz et al., 1997; Perrin et al., 2003; Barbieri et al., 2005). Sediment measurements in karst aquifers are typically performed by scraping cave surfaces, pumping or coring at well sites, automated pump sampling at spring outlets (Mahler et al., 1999; Herman et al., 2008; Reed et al., 2010), and use of sediment fingerprinting techniques for distinguishing sediment sources and estimating residence time (Mahler et al., 1998; Pronk et al., 2006).

In the present paper, the authors apply the above mentioned data collection methods and also work to extend the karst scientific toolbox in order to understand sediment carbon fate. The authors apply carbon stable isotopes for understanding the source of sediment carbon supplied to the karst subsurface *via* swallets and for investigating the fate of carbon within the subsurface. The stable isotopic signature of carbon ($\delta^{13}C$) is inherently linked to the land use origin of sediment from different plant type and management scenarios (Fox and Papanicolaou, 2008) as well as to the organic matter structure of carbon due to its sensitivity to the level of microbial processing (Acton et al., 2013). Carbon stable isotopes have been previously used in fluvial environments for understanding the source and fate of sediment carbon as well as within sediment fingerprinting (Fox and Papanicolaou, 2007; Fox, 2009; Jacinthe et al., 2009; Mukundan et al., 2010; Ford and Fox, 2015; Fox and Martin, 2015). However, to the authors' knowledge, the method has not been applied in karst settings. In addition to the use of stable isotopes and traditional sampling methods, the authors install several monitoring wells which directly intersect the primary karst at its longitudinal midpoint in order to continuously monitor water and sediment. The authors find few studies in the literature that have continuously collected hydrologic data at karst inlets and outlets as well as from within the primary conduit draining the aquifer.

This study's objectives were to elucidate previously unstudied hydrological processes within phreatic karst and develop a conceptual model of sediment carbon fate within phreatic karst. The conceptual model is discussed in the context of active freshwater carbon cycles. Thereafter, the conceptual model is used as a guide to build a numerical model in our companion paper (Paper 2: Numerical Model) that immediately follows this article in this journal.

2. Methods

2.1. Conceptual model development

The authors focus their conceptual model development for sediment carbon in phreatic karst upon hydrologic and landscape features that provides a sub-classification of karst systems (see Fig. 1). The authors emphasize mature, phreatic karst systems with hydraulically connected surface water and subsurface water. Sinking streams and swallets located in the surface stream corridor are fluviokarst features that can transport stream sediment to subsurface conduits and caves. The authors focus on phreatic karst such that a subsurface hydraulic control has the potential to mediate fluid energy, cause trapping of sediments, and potentially allow for the mineralization of sediment carbon. The authors emphasize karst systems with active subsurface conduit flow that can convey sediment to a springhead. The existence of a springhead allows connectivity of sediment carbon back to the fluvial network, which highlights the broader goal of understanding karst landscapes within the fluvial carbon cycle. Many phreatic karst systems reported upon in the literature can be characterized by the features mentioned above and conceptualized in Fig. 1 (White, 2002; Drysdale et al., 2001; Massei et al., 2003; Herman et al., 2008), yet sediment carbon fate and transport is understudied in such phreatic systems.

With the mentioned hydrologic and geologic characteristics in mind, the authors chose a mature karst system to assist with the conceptual model development for sediment carbon in phreatic karst. The study site chosen is the coupled Cane Run Creek Watershed and Royal Springs Groundwater Basin located in the Bluegrass