From the Mountains to the Sea: Interdisciplinary Science and Applications Driven by the Flow of Water, Sediment, and Carbon II

1. Science Targets and Importance to Decadal Survey Themes

The cycling of water, carbon, and sediment constitute core processes that help to define and sustain Earth's climate, landscape, and ecosystems. Outside of heavily glaciated regions and ignoring the smaller submarine groundwater discharge along the coast¹, these large mass fluxes primarily occur through the terrestrial networks of rivers and lakes, which are also key areas of societal concern due to their central roles in water resources, flood hazards, and ecosystem services. As rivers flow through landscapes, their loads of water, sediment, and carbon change through interaction with sources and sinks associated with natural processes and human activity [Fig 1]. With the discharge of water to the coast, large amounts of carbon and sediments are deposited into the ocean margin, reshaping the coastline and its ecosystems through processes that involve currents, waves, tides and organisms. To date, a great deal of research has focused on vertical land-atmosphere and oceanatmosphere fluxes of water and carbon, while the lateral transport of carbon, water and sediment from continental interiors to coastal oceans remain uncertain². Thus, to further constrain the water, carbon, and sediment budgets, and to understand their role and impacts on landscapes and ecosystems, it is imperative to improve our scientific understanding of their joint lateral fluxes at regional, continental, and global scales. Despite the importance of measuring water, carbon, and sediment, our *in situ* observing network is in decline³ [e.g. Fig 2] and the associated lack of measurements forestalls addressing scientific challenges, hinders management decisions, and limits our ability to evaluate policy effectiveness⁴. Remote sensing offers an efficient technology to provide unprecedented measurement capabilities that promise to improve scientific understanding of these complex systems, and provide key measurements on decision-relevant time scales to support sustainable management of resources⁵.

In our response to the first Decadal Survey RFI⁶, we identified a key overarching science question linking the three important fluxes identified above:

How is the transport of water, sediment, and carbon through the terrestrial surface water network and coastal oceans modulated by natural forcings and altered by human activities, and how are these associated changes affecting the human, biological, and geophysical systems?

Current technology is unable to provide answers to this question globally because (a) simultaneous measurements of water flux and sediment and carbon concentrations are limited to field measurements (stations and ship tracks) and are not spatially distributed; and (b) there is no space-based instrument capable of reliably detecting sediment and carbon in coastal and inland waters at a spatial resolution sufficient to most rivers. Addressing this key question will lead to enhanced scientific understanding of the water, carbon and sediment cycles and to better management of anthropogenic uses and disturbances. We further identify two science and applications targets:

- 1. Understand the human and natural forcings that distribute water, suspended sediment, and organic carbon in inland waters and coastal environments.
- 2. Further constrain the terrestrial and oceanic water, carbon, and sediment budgets by quantifying lateral transport from continental interiors to coastal oceans.

These objectives stem directly from the community priorities of hydrology, biogeosciences, coastal oceanography, and Earth surface processes. Although they are addressed in many community reports and roadmaps, we focus on a few key guiding documents here. In hydrology, a 2012 National Research Council study, *Challenges and Opportunities in the Hydrologic Sciences*, asks as one of its central questions "How do hydrologic systems, landscapes, and their biological communities co-evolve?"⁷. It specifically identifies better understanding of spatial patterns in runoff-generating processes as an area ripe for advance. Meanwhile, the Earth surface processes community, in a 2010

NRC study entitled *Landscapes on the Edge*⁸ identifies key questions that directly relate to our two objectives, including "How do ecosystems and landscapes coevolve?" and "What are the transport laws that govern the evolution of the Earth surface?" The *US Carbon Cycle Science Plan* (2011) identifies development of process level understanding of carbon fluxes in terrestrial and coastal regions as a high priority. More recently, the U.S. Carbon Cycle Program coordinated by the Ocean Carbon & Biogeochemistry (OCB) Program and the North American Carbon Program (NACP) published, in 2014, the *Science Plan for Carbon Cycle Research in North American Coastal Waters*⁹. Among other recommendations, the synthesis plan suggests an "Increased use of satellite products and development of algorithms for key carbon flux estimates (e.g., primary productivity and surfacewater *p*CO2) are needed, especially observations from high spatial and high temporal resolution satellite sensors." We propose to address these priorities by studying lateral exchanges of water, carbon, and sediment through the continuum of land, fresh water systems, and the coastal ocean.

The science and applications questions identified here inextricably link the interests of three separate decadal survey panels: I. Global Hydrological Cycles and Water Resources, III. Marine and Terrestrial Ecosystems and Natural Resource Management, and V. Earth Surface and Interior. Understanding of the global water cycle and water resources is incomplete without taking into account river discharge, lake water storage, and the transport of fresh water from land to oceans. Marine, aquatic, and terrestrial ecosystems drive the generation and processing of organic carbon, and an improved quantification of the carbon cycle is a key part of understanding these systems. The erosion, transport, and deposition of sediment is the fundamental concern of Earth surface processes and drives building and maintenance of coastal environments such as river deltas. This response therefore cuts across three panels, as it does across the community roadmaps highlighted above.

2. Measured Geophysical Variables.

Water acts as a conveyor transporting material, including carbon and sediment, from the land to the coast and within the oceans. As such, improved knowledge of water fluxes, and measurements of organic carbon and sediment concentrations within the water would enhance our understanding of their lateral fluxes. These lateral fluxes can then be combined with vertical land-atmosphere and ocean-atmosphere fluxes to better constrain each cycle. While in situ measurements of water flux and organic carbon and sediment concentration are necessary, closing their budgets could only be achieved with **frequent**, **simultaneous**, **and spatially-distributed measurements of volumetric fluxes of water**, **sediment**, **and carbon**. Remote observations could enable such measurements globally. A summary of the geophysical variables to be measured in order to estimate the horizontal fluxes of water, organic carbon, and sediment is provided in Table 1.

Measurement of river discharge from space has received considerable attention over the last 20 years. Early methods demonstrated that it is possible to estimate discharge based on remote measurements of inundation extent¹⁰ and water surface elevation¹¹, provided sufficient ground-based measurements are available to develop a rating curve. Unfortunately, these ground-based measurements are not widely available in many parts of the world, and other satellite-based approaches require more complex models and assumptions that often add considerable uncertainty¹². More recently, work performed in preparation for the Surface Water and Ocean Topography (SWOT) mission, advanced during the 2007 NRC Decadal Survey and planned to launch in 2021, has demonstrated several methods for estimating discharge without need for ground-based measurements^{13–15}. When compared across a wide range of rivers, initial analysis suggests that, given the kind of data SWOT will provide in rivers (e.g. river width, height, and slope), it may be possible to measure discharge with accuracy better than 35% in most river systems using current techniques¹⁶. This recent work, which continues to evolve and improve, suggests that robust estimation of discharge from space in wide rivers (~100m) is likely to become a reality with the advent of SWOT.

Measurement of coastal oceanic processes from space has received relatively less attention, though many of the key biological and sedimentary processes occur in the near-coastal zone. Most sediment deposition even in the largest river deltas occurs within a few hundred km of river mouths¹⁷. Recent reviews of coastal carbon cycling have indicated substantial variability in the seato-air fluxes of carbon dioxide (CO₂) that is likely linked to the fate of dissolved organic carbon (DOC) in coastal waters as contributed by estuaries and coastal marshes and wetlands¹⁸. Coastal circulation is driven by currents, which result from combined effects of winds, waves, tides, river discharge and topography, factors that in turn determine the fate of water, carbon and sediment. The complex physical processes involved make it difficult to estimate coastal currents from measurements of water surface elevation alone (e.g. SWOT). However, tidal levels associated with topography are some of the most significant drivers of coastal ecosystem productivity and hence of these ecosystems' ability to capture sediment and carbon¹⁹ because they together determine the inland reach of ocean water. The SWOT mission is expected to enable the first globally consistent measurements of sea level and tides around the world's coasts. Simultaneous optical observations of plumes, combined with water surface topography and hydrodynamic models, could be used to infer oceanic transport of water, organic carbon, and sediment, and provide useful information about the patterns of sediment and carbon transport in these environments.

In both terrestrial and oceanic waters, measurements of water surface reflectance can be used to estimate the concentrations of suspended sediments. Although it is not possible to measure all components of sediment transport via remote sensing, numerous studies have shown that it is possible to estimate the suspended sediment concentration (SSC) using optical imagery²⁰⁻²⁴. Because suspended loads often represents 70-90% of the total sediment transport in alluvial rivers²⁵, a robust estimation would provide a useful constraint on total sediment transport. Most methods for remote retrieval of SSC have been developed for regional application using existing space-borne sensors such as Landsat²⁶, ASTER²⁷ and MODIS²⁸. Few attempts have been made to transfer SSC-reflectance relationships between regions, though recent results suggest that such transfer may be possible under some conditions²². Such transferability is particularly likely if hyperspectral imagery is available, as subtle regional differences in sediment color can be taken into account.

Measurements of surface water reflectance can also be used to estimate the concentration of chromophoric (colored) dissolved organic matter (CDOM), which makes up a substantial fraction – albeit variable – of dissolved organic carbon and is a better tracer than chlorphyll-a in riverine and coastal waters²⁹. CDOM represents the fraction of the bulk dissolved organic matter (DOM) pool that absorbs light in both visible and ultraviolet (UV) ranges³⁰. In coastal waters, where riverine input is significant, CDOM is primarily derived from terrestrial sources³¹. This fraction of DOM is of particular interest to researchers due to its particular optical characteristics, which are important to processes that can affect biogeochemistry and the ecological health of the aquatic environment. CDOM strongly absorbs light in the visible and UV range, and thus plays a key role in controlling light penetration in the water column, as well as the quantity and quality of photosynthetic active radiation (PAR). The photoreactivity of CDOM leads to the formation of a variety of compounds, which can then influence aquatic biogeochemistry, carbon cycling, and atmospheric chemistry³². Quantifying C fluxes to coastal waters from remote sensing observations has been primarily focused on riverine discharge because terrestrial sources often dominate these systems. In addition, the contribution of CDOM to DOC can be as high as 70% in the ocean³³. Thus, recent evidence suggests that it is likely possible to use CDOM as a proxy for terrestrial organic matter drainage to coastal waters³⁴ and then develop relationships between remote sensing reflectance and CDOM, producing a bio-optical model for DOC concentration³⁵. Several studies have published such algorithms for distinct coastal regions, e.g., Gulf of Mexico³⁶ and US Middle Atlantic Bight³⁷. Finally, while the relatively more diluted dissolved inorganic carbon (DIC) would not be captured here, the aforementioned suspended sediment measurements could help estimate particulate organic carbon.

3. Key Measurement Requirements.

The required accuracy of individual measurements depends on the current state of knowledge of the relevant cycle (water, carbon, or sediment). None of these are currently well-quantified, especially regarding their variability in time, although there is considerably more heritage in quantification of water fluxes compared to sediment and carbon fluxes. Focusing on the transport of water and its constituents through the river systems to the ocean may not directly identify and quantify the sources and sinks, but it will identify key locations of water, sediment, and carbon inflow and outflow from the system and will enable estimation of fluxes between land and sea. To this end, we define two quantifiable Earth science objectives (QESOs):

- Measure the flux of water through the regional-scale terrestrial river network to +/-20% accuracy at monthly time scales.
- Estimate the lateral fluxes of sediment and carbon through the regional-scale terrestrial river network and adjacent ocean environments to within +/-50% at monthly timescales.

In the case of the terrestrial water cycle, the required accuracy is based on errors in runoff calculated from global hydrologic models, which are commonly 40% or higher^{38,39}. Discharge measurements with errors less than 20% would substantially constrain the output of these models by approximately halving the overall uncertainty in model-generated discharge. This advance is particularly important in the ~40% of river basins draining to oceans that are entirely ungauged. At present, the only alternative is to use uncalibrated land surface models that produce major uncertainty, especially in South Asia, South America, Oceania and Central Africa⁴⁰. The proposed discharge measurements could then be associated with computer models of the global terrestrial water cycle through data assimilation. Such process would fill in the blanks in space and time between observations and produce continuous discharge estimates while remaining consistent with available observations.

Because the fluxes of carbon and sediment are estimated by combining a flux of water with a concentration of carbon or sediment, uncertainty in the flux of water propagates into error for the other two variables. In the case of sediments, even the total annual flux of sediment from the land surface into the global ocean is not well constrained, though various estimates exist². With the exception of a limited range of large river systems [e.g. the Mississippi and Amazon], high frequency temporal variations are rarely available. As such, constraining spatial and temporal variations in sediment flux even to within a factor of two would be a breakthrough. In the case of carbon, the lateral flux across the continents should close the budget between land-atmosphere and ocean-atmosphere exchanges⁴¹. As we strive to understand how human activity alters the global carbon cycle, tracking fluxes of carbon through rivers and other pathways becomes increasingly important⁴². At present, carbon fluxes through many of the world's rivers and between coastal wetlands and adjacent oceans remain poorly monitored, and constraining variations in carbon transport to within a factor of two would be a substantial advance⁴³.

The required temporal frequency of measurements depends primarily on the temporal variability of the phenomena to be measured. This variability itself is not constant in space. For example, large rivers like the Amazon vary primarily on seasonal timescales, while smaller rivers can vary on sub-daily timescales. As an example, Fig. 3 shows the variability in sediment load, suspended sediment concentration, and discharge for the Sacramento River (California) over a 10-year period. Although seasonal patterns are evident, much of the variability in sediment occurs on daily to weekly timescales. Observations once per week would allow at least one measurement of major flood events on medium-sized rivers like the Sacramento, while allowing temporal dynamics to be sensed on large rivers like the Mississippi, where flood waves often encompass 4-6 weeks. This work suggests that the temporal sampling interval must be weekly or better. While finer temporal resolutions would allow measurement of processes in smaller rivers with very rapid

response times to storm events, such measurements are unlikely to be achieved affordably in the next decade. As such, an essential component of closing these budgets will be assimilation of satellitederived data into Earth system models that fill in the gaps between observations that constrain them.

Finally, spatial resolution requirements depend largely on our ability to measure flow through comparatively narrow rivers. We require sub-hectometer (10-100 m) native spatial resolutions, which will allow measurement of rivers as narrow as 50-100 m. Coarser spatial resolutions would allow measurement of only the largest rivers. These requirements are summarized in Table 1.

4. Affordability

An ideal system would involve two instruments: a radar sensor, which to constrain costs could be a copy of SWOT, paired with a high spectral resolution optical sensor designed to optimize estimation of suspended sediment concentration and CDOM. Because the two sensors in question have significant yet different power and data rate constraints, it is likely that two separate satellites would represent a more robust solution without adding enormously to overall cost. Such a mission would enable simultaneous satellite-derived measurements of river discharge and sediment/carbon concentration in rivers and coastal oceans. Measurement of volumetric water fluxes can be achieved by leveraging technology and algorithms currently under development for the SWOT mission, for which estimation of discharge and ocean circulation are primary goals⁴⁴. The primary instrument on SWOT is a Ka-band radar interferometer (KaRIn) that will measure water surface elevation and inundation extent in two 50 km swaths on either side of the satellite nadir track (Fig. 4).

Meanwhile, remote estimation of sediment and CDOM concentrations using optical instruments has a long heritage in both freshwater and oceanic environments. Modern spectroscopic measurements can be achieved affordably in the decadal timeframe due to investments in response to global terrestrial/coastal coverage missions outlined in the 2007 NRC Decadal Survey and NRC Landsat and Beyond report and elsewhere. These measurements build on a legacy of instruments including airborne: AIS⁴⁵, AVIRIS⁴⁶, and AVIRIS-NG⁴⁷ and spaceborne: NIMS⁴⁸, VIMS⁴⁹, Deep Impact⁵⁰, CRISM⁵¹, EO-1 Hyperion^{52,53}, M3⁵⁴, and MISE, the imaging spectrometer now being developed for NASA's Europa mission. NASA-guided engineering studies in 2014 and 2015 show that a VSWIR (380 to 2510 nm $@\leq 10$ nm sampling) [Fig. 5] imaging spectrometer instrument with a 185 km swath and 30 m spatial sampling with high signal-to-noise ratio (SNR) and the required spectroscopic uniformity can be implemented affordably for a three year mission with mass (98 kg), power (112 W), and volume compatible with a Pegasus class launch. To meet the requirements of this science objective, the swath can be widened to 370 km with 60 m sampling to provide ~weekly revisit. The key for this measurement is an optically fast spectrometer providing high SNR and a design that can accommodate the full spectral and spatial ranges⁵⁵. A scalable prototype F/1.8 full VSWIR spectrometer⁵⁶ with full spectral range CHROMA detector array has been developed, aligned, and is being qualified [Fig 6]. Data rate and volume challenges have been addressed by development and testing of a lossless compression algorithm for spectral measurements^{57,58}. With compression and the current Ka-band downlink offered by KSAT and others, all terrestrial/coastal measurements can be downlinked. To enhance affordability and accelerate measurement availability, there is good potential for shared launches, spacecraft, and international partnerships.

Flying in formation, a build to print SWOT-like radar interferometer and an imaging spectrometer would be achievable affordably due to the considerable heritage for both instruments. This combined system would allow simultaneous estimation of water flux and sediment/carbon concentration, thus addressing our science and applications objectives. Moreover, a final key asset in achieving these goals is a potential collaboration with CNES, the French space agency. NASA and CNES have partnered on a long series of altimetric missions beginning with Topex/Poseidon and extending through SWOT. Extending this partnership would be advantageous for both countries by sharing mission costs and complementary expertise.

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Zone	Desired spatial scales	Desired geophysical variable	Intermediate geophysical variable	Intermediate equation	Error requirement	Measured geophysical variables	Measured spatial resolution	Measured temporal resolution
Within the terrestrial system	Rivers wider than 100m, Lakes larger than 0.1 km ²	$Q_W^R[kg/s]$	-	-	Q_W^R +/- 20%	H_W^R , A_W^R	10-100m	Weekly
		$Q_C^R [kg/s]$	$C_C^R [kg/kg]$	$Q_C^R = C_C^R * Q_W^R$	C _C ^R +/- 50%	λ_{C}^{R}	30-60-m	
		$Q_{S}^{R} [kg/s]$	C_{S}^{R} [kg/kg]	$Q_S^R = C_S^R * Q_W^R$	C _S ^R +/- 50%	λ_{s}^{R}	30-60-m	
Within the coastal interface	Estuaries, deltas, wetlands, 1 km ²	M_W^{I} [kg]	-	-	${M_W}^I$ +/- 20%	H_W^{I} , A_W^{I}	10-100m	
		$M_{C}^{I}[kg]$	$C_C^R [kg/kg]$	$M_C^{I} = C_C^{I} * M_W^{I}$	C _C ^I +/- 50%	λ_{C}^{I}	30-60-m	Weekly
		$M_{S}^{I}[kg]$	C_{S}^{R} [kg/kg]	$M_S^{I} = C_S^{I} * M_W^{I}$	C _S ^I +/- 50%	λ_{s}^{I}	30-60-m	
Within the coastal ocean	Coastal zones larger than 1 km ²	$M_W^O[kg/s]$	-	-	${\rm M_W}^{\rm O}$ +/- 20%	H_W^{O} , A_W^{O}	10-100m	
		$M_C^O[kg/s]$	$C_C^R [kg/kg]$	$M_{C}^{O} = C_{C}^{O} * M_{W}^{O}$	C _C ^O +/- 50%	λ_{C}^{O}	30-60-m	Weekly
		$M_{s}^{O}[kg/s]$	C _S ^R [kg/kg]	$M_{S}^{O} = C_{S}^{O} * M_{W}^{O}$	C _S ^O +/- 50%	λ_s^{O}	30-60-m	

Table 1. Summary of desired and measured quantities along with error requirements. Notations: Geophysical variables are the following: mass (M), mass flow rate (Q), elevation of surface (H), inundated area (A), reflectivity (λ), mass concentration (C). Subscripts are used for water (w), carbon (c), and sediment (s). Superscripts are used for zones: rivers and lakes (R), coastal interface (I), coastal ocean (O).



Figure 1: Conceptual figure showing source to sink transport of water, sediment, and carbon.



Figure 2: River discharge data in the Global Runoff Data Centre. Note the precipitous decline beginning around 1980⁵⁹.

Sacramento time series



Figure 3: Time series of sediment transport, SSC, and discharge for the Sacramento River (California) over 10 years.



Figure 4: SWOT mission concept, with two 50 km measurement swaths, each of which will produce maps of water surface elevation and inundation extent⁴⁴.



Figure 5: Contiguous spectral coverage from 380 to 2510 nm of the F/1.8 VSWIR Dyson showing overlap with LandSat and Sentinal-2 bands. Such a sensor would provide a great deal more information than multispectral instruments.





Figure 6: (top) Design of F/1.8 VSWIR Dyson covering the spectral range from 380 to 2510. (right) Dyson spectrometer with CHROMA full range detector array that is in qualification.

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Summary

The transport of material through river networks and into the coastal oceans is a key, underobserved component of global water, sediment, and carbon cycles. A radar interferometer combined with an imaging spectrometer would affordably measure water flux and sediment/organic carbon concentrations, allowing improved understanding of these cycles.