AN ABSTRACT OF THE DISSERTATION OF

Laurel E. Stratton Garvin for the degree of Doctor of Philosophy in Water Resources Science and Geology presented on April 23, 2018.

Title: A Stratigraphic Approach to Characterize the Deposition and Storage of Organic Matter in Reservoir Sediments.

Abstract approved: ____

Roy Haggerty   Gordon E. Grant

The relationship between carbon burial and sedimentation in reservoirs is unknown, exposing gaps in our fundamental understanding of the transport, processing, and deposition of sediment and organic matter in fluvial and lacustrine systems and contributing to uncertainty in our understanding of the net impact of dams to the global carbon budget. The 2011-2014 removal of two large dams on the Elwha River, Washington State, the largest dam removal yet completed globally, created extensive cutbank exposures of reservoir sediments, allowing the first characterization of the facies architecture of sediments through direct observation in reservoirs worldwide and providing an unparalleled opportunity to 1) assess the relationship between environmental influences, such as and changes in sediment supply, and their expression in the stratigraphic record, 2) assess the relationship between sedimentation processes and detrital organic carbon deposition and storage, and the importance of coarse-grained organic matter and woody debris to the total carbon budget of a reservoir, and 3) apply the insight gained from these reservoirs to evaluate current global estimates of carbon storage in reservoirs and develop a conceptual model of carbon burial in reservoirs to guide further research, as defined by characteristic stratigraphic "types".

Former Lake Mills, the younger, upstream reservoir, was characterized by a tripartite, subaerial Gilbert-style delta which prograded >1 km into the main reservoir from 1927 to 2011. Sediments were composed of coarse-grained topset beds, steeply

dipping foreset beds, and a fine-grained, gently dipping prodelta. While individual event horizons were discernible in fine-grained sediments of former Lake Mills, their number and spacing did not correspond to known drawdown or flood events. Former Lake Aldwell, impounded from 1913 to 2011, was initially defined by the rapid progradation of a Gilbert-style, subaerial delta prior to the upstream completion of Glines Canyon Dam. However, the 1927 closure of Glines Canyon Dam upstream caused the delta to evolve to a fine-grained, mouth-bar type delta indicative of low, finer-grained sediment. This evolution, combined with a previously-unrecognized landslide deposit into the upper delta plain, suggests that understanding the exogenic influences on reservoir sedimentation is critical to interpretation and prediction of the sedimentation within individual systems.

Former Lake Mills accumulated ~330 Gg of, with depositional-zone average accumulation rates from 229 to 9262 $gCm^{-2}yr^{-1}$, while Former Lake Aldwell accumulated ~ 91 Gg (263 to 2414 $gCm^{-2}yr^{-1}$). Carbon storage in both reservoirs was dominated by heterogeneous, coarse organic matter and woody debris in the coarse-grained delta slope and relatively coarse-grained prodelta regions of the reservoirs, with little storage in the gravel-dominated, subaerial delta plains. Carbon accumulation in fine-grained lacustrine and prodelta sediments was relatively homogeneous, but turbidity flows from the Gilbert-style delta slope in former Lake Mills delivered significantly more carbon to the prodelta than the mouth-bar style delta of former Lake Aldwell. C:N ratios support interpretation of most organic matter in both reservoirs as allochthonous. Sampling schemes based only on lacustrine and/or prodelta would underestimate of total carbon accumulation by up to 30% in former Lake Aldwell, but the overestimate by up to 47% in former Lake Mills.

Global estimates of carbon sequestration rates in reservoir sediments vary by three orders of magnitude, while individual-reservoir estimates vary by four orders of magnitude and over only 37 reservoirs and a literature review of predictive variables suggests weak or contradictory relationships. A conceptual stratigraphic framework of four unique reservoir types suggests that organic matter deposition is intrinsically tied to sedimentation processes and that patterns of carbon storage vary systematically with the stratigraphy of reservoir sediments. Deltaically-dominated reservoirs (whether Gilbert style or shoalwater) appear to store most carbon in their deltaic and prodelta regions, while thalweg-style reservoirs exhibit a bimodal distribution, with allochthonous carbon preferentially routed along the former river thalweg and autochthonous deposited on the former floodplain. Lacustrine-style reservoirs are dominated by suspended sediment deposition and thus relatively homogeneous, but literature suggests these reservoirs are more variable than typically measured. Current methods of reservoir sampling fail to account for this systematic variation and tend to be biased toward fine sediment, suggesting that global reservoir carbon storage is underestimated.

A STRATIGRAPHIC APPROACH TO CHARACTERIZE THE DEPOSITION AND STORAGE OF ORGANIC MATTER IN RESERVOIR SEDIMENTS

by
Laurel E. Stratton Garvin

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented April 23, 2018
Commencement June 2018

Doctor of Philosophy dissertation of Laurel E. Stratton Garvin presented on April 23, 2018

APPROVED:

Co-Major Professor, representing Water Resources Science

Co-Major Professor, representing Geology

Director of the Water Resources Graduate Program

Dean of the College of Earth, Ocean, and Atmospheric Sciences

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Laurel E. Stratton Garvin, Author

ACKNOWLEDGEMENTS

Funding for this work was provided by the HydroResearch Foundation and Oregon State University in the form of multiple fellowships and assistantships.

I wish to express my gratitude to my advisors, Roy Haggerty and Gordon Grant, for their committed guidance, sharp insight, and intellectual rigor, and to my committee members, Miguel Goñi and Rob Wheatcroft, for their generosity with their time, insight, and laboratories. I thank Sarah Lewis for her managerial skills, editorial eye, and generous spirit, without which I would probably not have completed this dissertation. I also thank Mary Santelmann for her encouragement, stern belief in her students' excellence, and tireless efforts to shepherd the Water Resource Program to continued success.

My supervisors and colleagues at the USGS Oregon Water Science Center, in particular Rose Wallick, Stewart Rounds, and Mackenzie Keith, and my supervisors and colleagues at the U.S. Environmental Protection Agency National Health and Environmental Effects Research Laboratory, including Scott Leibowitz and Randy Comeleo, were invaluable in their encouragement, flexibility, and mentoring as I worked to balance my academic and professional obligations throughout my time at Oregon State University. I also extend my gratitude to the many, many friends and colleagues who generously shared their time, ideas, and humor to help with everything from data collection to finding the fun in graduate school.

Finally, I thank my wonderful family—most particularly, my husband Paul -- for their inspiration, faith, and grounding influence.

CONTRIBUTION OF AUTHORS

Dr. Roy Haggerty provided structure and guidance in the initial framing of this dissertation and the mathematical conception of carbon cycling and controls on burial efficiency in reservoirs sediments. Dr. Gordon E. Grant provided conceptual and editorial support on all manuscript drafts.

TABLE OF CONTENTS

1 Introduction 1

1.1 References Cited 5

2 Autopsy of a Reservoir: Facies Architecture in a Multi-Dam System, Elwha River, Washington, USA 9

2.1 Abstract 10
2.2 Introduction 10
2.3 Approach and Scope 13
2.4 Study Area 14
2.4.1 Elwha River Hydrology and Geomorphology 14
2.4.2 Reservoir Descriptions and Project History 16
2.5 Data Collection and Analysis 18
2.5.1 Mapping and Watershed Analysis 18
2.5.2 Stratigraphic Descriptions 19
2.5.3 Sedimentation Rates and Reservoir Accumulation Volumes 20
2.6 Results: Depositional Characteristics of the Former Reservoirs 21
2.6.1 Lake Mills 21
2.6.2 Lake Aldwell 29
2.7 Discussion 36
2.7.1 Lake Mills 36
2.7.2 Lake Aldwell 40
2.8 Summary and Conclusions 44
2.9 Acknowledgements 47
2.10 References Cited 48
2.11 Figures 56
2.12 Tables 72
2.13 Supplementary Information 76

3 Stratigraphic-Based Analysis of Organic Matter Deposition in Two Former Hydropower Reservoirs: The Importance of Coarse Organic Matter to Carbon Loads and Burial in Artificial Impoundments in Mountainous Environments 77

TABLE OF CONTENTS (Continued)

3.1 Abstract 78
3.2 Introduction: carbon accumulation in reservoirs 78
3.3 Study Area 82
3.3.1 Elwha Watershed 82
3.3.2 Elwha Reservoirs 83
3.4 Methods 84
3.5 Results 85
3.5.1 A stratigraphic approach to the deposition of organic matter 85
3.5.2 Organic matter provenance 93
3.5.3 Carbon accumulation by depositional zone: toward quantification of carbon storage 95
3.6 Discussion 96
3.7 Conclusions and Implications 101
3.8 Acknowledgements 102
3.9 References Cited 103
3.10 Figures 112
3.11 Tables 117
3.12 Supplementary Information 124

4 A stratigraphic framework to evaluate the deposition and burial of organic matter in reservoir sediments 127

4.1 Abstract 128
4.2 Introduction 128
4.3 Current estimates of carbon burial 130
4.3.1 Continental- to global-scale averages 130
4.3.2 Individual reservoir estimates 132
4.4 Assessing burial estimates 133
4.4.1 Approaches and assumptions 134
4.4.2 Processes and form 136
4.5 Stratigraphic frameworks: connecting form to process 137
4.5.1 Gilbert Style 138

TABLE OF CONTENTS (Continued)

4.5.2 Shoal-water 139

4.5.3 Thalweg.. 140

4.5.4 Lacustrine.. 142

4.6 Discussion 144

4.7 Conclusions 147

4.8 Acknowledgements 148

4.9 References Cited 149

4.10 Figures.. 157

4.11 Tables 161

4.12 Supplementary Information.. 163

5 Conclusions 165

LIST OF FIGURES

Figure 2-1. Map showing location of Elwha watershed on the Olympic Peninsula of western Washington State. 56

Figure 2-2. Hydrographs of the Elwha River at McDonald Bridge (USGS gaging station 12045500). 57

Figure 2-3. Delta morphology, 2009 (A), sediment accumulation, dam closure to 2010 (B), and stratigraphic section location (black crosses), 2014 (C). 58

Figure 2-4. Dam crest and water surface elevations during stepped removal of Glines Canyon (A) and Elwha (B). 59

Figure 2-5. Thalweg profiles showing: A) Elwha River gradient, Mount Olympus to river mouth at Strait of Juan de Fuca. Dams indicated in green (Glines Canyon) and yellow (Elwha); shaded area indicates length of reservoir B) Profile of Lake Mills and C) Profile of Lake Aldwell. 60

Figure 2-6. Geomorphic map of Lake Mills (A) and Lake Aldwell (B) based on 2006 and 2009 aerial photographs. 61

Figure 2-7. Relative subaerial delta progradation rate and morphology, Lake Aldwell (above) and Lake Mills (below).. 62

Figure 2-8. Representative stratigraphic sections within geomorphic depositional zones, former Lake Mills.. 63

Figure 2-9. Idealized stratigraphic columns, former Lake Mills 64

Figure 2-10. Conceptual, cartoon model of cross-sectional sedimentation patterns in former Lakes Mills (A) and Aldwell (B). 65

Figure 2-11. Evidence of extensive upper delta plain development in former Lake Aldwell early in the reservoir history 66

Figure 2-12. Representative stratigraphic sections within geomorphic depositional zones, former Lake Aldwell. 67

Figure 2-13. Idealized stratigraphic column, former Lake Aldwell 68

Figure 2-14. Photographic panorama and cartoon showing Gilbert-style progradation in former Lake Aldwell. 69

Figure 2-15. Photograph with cartoon depicting sandy interbeds in lacustrine basin of former Lake Mills. 70

Figure 2-16. Map depicting 78% reduction in bedload source area to Lake Aldwell before (A) vs. after (B) the closure of Glines Canyon Dam (1927)..................................... 71

Figure 3-1. Location of former Lakes Aldwell and Mills in the Elwha River watershed, Clallam County, Washington.. 112

Figure 3-2. Depositional zones and sampling locations.. 113

Figure 3-3 Composite stratigraphic columns, former Lakes Mills (A) and Aldwell (B).. 114

Figure 3-4. Whisker plot of prodelta and basin facies wt% TOC (A) and C:N ratio (B) in former Lake Mills. 115

Figure 3-5. A) Relationship between TOC and C:N by depositional zone. 116

Figure 4-1. Area-weighted estimates of carbon burial in sediments of individual reservoirs included in Table 2 (open circles) vs. global distribution of dams in GranD Database (dots; Lehner et al., 2011) 157

Figure 4-2. Conceptual stratigraphic framework of four 'typical' reservoir types... 158

Figure 4-3. Examples of coarse organic matter deposition in A) Lake Mills (Elwha River), showing prodelta sands (A1), foreset beds (A2), B) Lake Aldwell (Elwha River), showing delta mouthbar sands (B1 and B2) and C) Fall Creek Reservoir (Fall Creek), showing horizontally-laminated coarse organic matter along Fall Creek thalweg... 159

Figure 4-4. Total organic carbon and C:N ratios in cores collected from Lake Billy Chinook.. 160

LIST OF TABLES

Table 2-1. Morphological and timeline comparison between former Lakes Aldwell and Mills. 72

Table 2-2. Facies designations, former Lakes Aldwell and Mills. 73

Table 3-1. Facies designations, former Lakes Aldwell and Mills.. 118

Table 3-2 . Analytical carbon content data by facies.. 122

Table 3-3. Depositional volumes and estimated area-weighted carbon accumulation rates.. 123

Table 4-1. Continental- and global-scale estimates of carbon burial in reservoir sediments........ 161

Table 4-2. Categorization of typical assumptions and limitations by sampling method and sampling distribution. 162

LIST OF SUPPLEMENTARY FIGURES

Figure SI-2-1. Geology of the Elwha catchment depicting named tributaries to Lakes Aldwell and Mills. Geologic data after Schuster, 2005. 76

Figure SI-3-1. Examples of detrital organic-rich facies..124

LIST OF SUPPLEMENTARY TABLES

Table-SI-3-1. Type and degradation criteria to classify organic matter in section exposures....125

Table-SI-3-2. Reproduced data from Gilbert and Link (1995), recalculated as percent of total accumulation....126

Table-SI-4-1. Database of studies with estimates of whole-reservoir carbon burial.......163

1 Introduction

Transporting water, sediment, and nutrients while acting as sites of intense biogeochemical processing, rivers are a critical nexus of global geologic, hydrologic, ecologic, and atmospheric cycling. This cycling, however, has been profoundly impacted by the ongoing boom in dam construction, which now intercepts approximately 40% of global discharge, has increased the Earth's terrestrial water surface area by ~7.3%, and impounds as much as 25% of the global annual sediment delivery to the oceans (Vörösmarty et al., 2003, Syvitsky et al., 2005; Nilsson et al., 2005; Downing et al., 2006; Lehner et al., 2011). The resulting disconnectivity in the global transfer of sediment and nutrients in these "rivers of the Anthropocene" (Poff, 2014, pg. 427; c.f. Waters, 2016) has been the subject of much study, particularly in the estimation of the net sediment volume translocation (c.f. Walling and Fang, 2003; Vörösmarty et al., 2003; Syvitski et al. 2005; Kummu et al., 2010; Yang and Lu, 2014), the investigation of downstream geomorphic and ecologic adjustments (e.g., Nilsson and Berggren, 2000; Bunn and Arthington, 2002; Graf, 2005), and the production and emission of greenhouse gases from artificial reservoirs (c.f., Rudd et al., 1993; St. Louis 2000; Abril 2005; Guérin et al. 2006; Cole et al., 2007; Barros et al., 2011; Deemer et al., 2016).

However, given their global prominence, the depositional environments in reservoirs themselves have been the subject of relatively little study. Despite the thorough investigations of the basin- to global-scale impact of sediment retention behind dams (e.g., Minear and Kondolf, 2009), at the scale of individual dams, most effort has focused on developing approaches to help dam owners manage the negative impacts of sedimentation from a reservoir capacity perspective (c.f., Strand and Pemberton, 1987). Limited studies, based in the engineering literature, suggest a "typical" reservoir sediment profile defined by a tripartite structure consisting of "inflow", "transport", and "depositional" regions, with the inflow region defined by characteristic topset, foreset, and bottomset beds (c.f. Thornton et al., 1990; Morris and Fan, 1998). However, a variety of exo- and endogenic influences, ranging from watershed characteristics to operational regime, have been found to impact sedimentation patterns, and the connection between sedimentation processes and stratigraphic form in reservoirs remains poorly understood (c.f., Ambers, 2001; Snyder et al., 2004; 2006; Kondolf et al., 2014).

In addition to sediment-related implications of dams on river systems, evidence indicates that the increase in global terrestrial water surface area has impacted the carbon cycle on a global scale. Following the initial recognition that reservoir emit large volumes of greenhouse gases, intense study has been devoted to the quantification of the greenhouse gas impact of dams and to understanding the biogeochemical controls on elevated production of carbon dioxide and methane as compared to natural lake systems (St. Louis 2000; Abril 2005; Guérin et al. 2006; Tranvik et al., 2009; Jacinthe et al., 2012; Clow et al., 2015). Evidence shows that reservoirs are hotspots of biogeochemical activity as compared to natural systems, with intensified rates of nutrient cycling, including primary production, mineralization, and sedimentation (burial) (Cole et al., 2007; Maavara et al., 2017). However, most of this research has focused on the gross greenhouse gas footprint of reservoirs, with comparatively little investigation of the potential for carbon storage in the large volume of sediments held behind dams. The relationship between carbon burial and sedimentation in reservoirs remains poorly characterized, contributing to uncertainty in our understanding of the net impact of dams to the global carbon budget and exposing gaps in our fundamental understanding of the transport, processing, and deposition of organic matter in fluvial and lacustrine systems.

The increasing rate of intentional dam removals (O'Connor et al., 2015; Major et al., 2017), however, provides a unique opportunity to study these systems, exposing sediments and creating unmatched opportunities for the direct observation of fluviolacustrine environments. The 2011-2014 demolition of Glines Canyon and Elwha Dams on the Elwha River, Clallam County, Washington State, was the largest dam removal project yet undertaken globally, and, in contrast to other, smaller removal projects, was conducted over a period of time, allowing the Elwha River time to laterally migrate across the reservoir basin as it excavated sediments in response to the establishment of each new base level (Randle et al., 2015). Taking advantage of the combination of unparalleled exposures and intense scientific scrutiny such a novel project attracted, this work investigates the dynamics of sedimentation in former Lakes Mills and Aldwell (Chapter 2), then uses the stratigraphic framework developed to interpret patterns of carbon burial in each reservoir (Chapter 3), before building on the knowledge gained from these case studies to evaluate current estimates of carbon burial in reservoirs globally and suggest a stratigraphically-based conceptual model to further investigate these complex systems (Chapter 4).

1.1 References Cited

Abril, G., Guérin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., Tremblay, A., Varfalvy, L., Dos Santos, M. A., and Matvienko, B. (2005). Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana), *Global Biogeochemical Cycles* (19), GB4007, https://doi.org/10.1029/2005GB002457

Ambers, R.K. (2001). Using the sediment record in a western Oregon flood-control reservoir to assess the influence of storm history and logging on sediment yield. *Journal of Hydrology*, *244(3-4),* p. 181–200. https://doi.org/10.1016/S0022-1694(01)00331-6

Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M, del Giorgio, P. and F. Roland (2011). Carbon emissions from hydroelectric reservoirs linked to reservoir age and latitude. Nature Geoscience Letters 4.

Bunn, S.E., and Arthington, A.H., 2002, Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity: Environmental Management, v. 30, p. 492–507.

Clow, D. W., Stackpoole, S. M., Verdin, K. L., Butman, D. E., Zhu, Z. L., Krabbenhoft, D. P., and Striegl, R. G. (2015). Organic Carbon Burial in Lakes and Reservoirs of the Conterminous United States. Environmental Science & Technology, 49(24), 14741-14741. https://doi.org/ 10.1021/acs.est.5b00373

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Middelburg, J. J., and Melack, J. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. Ecosystems, 171-184. https://doi.org/10.1007/s10021-006-9013-8

Deemer, B. R., Harrison, J. A., Li, S. Y., Beaulieu, J. J., Delsontro, T., Barros, N., Bezerra-Neto, J. F., Powers, S. M., dos Santos, M. A., and Vonk, J. A., 2016, Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis. Bioscience, 66(11). 949-964. https://doi.org/10.1093/biosci/biw117

Downing, J.A., Prairie, Y.T., Cole, J.J., Duarte, C.M., Tranvik., L.J., Striegl, R.G., McDowell, W.H., Kortelainen, P., Caraco, N.F., Melack, J.M, Middelburg, J.J. (2006). The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography*, 51(5), 2388-2397. https://doi.org/10.4319/lo.2006.51.5.2388

Graf, W.L., 2005, Geomorphology and American dams: The scientific, social, and economic context: Geomorphology, v. 71, p. 3–26, doi: 10.1016/j.geomorph.2004.05.005.

Guérin, F., Abril, G., Richard, S., Burban, B., Reynouard, C., Seyler, P. and Delmas, R. (2006). Methane and carbon dioxide emissions from tropical reservoirs: significance of downstream rivers. *Geophysical Research Letters*, 33, 1-6. https://doi.org/ 10.1029/2006GL027929

Jacinthe, P. A., Filippelli, G. M., Tedesco, L. P., and Raftis, R. (2012). Carbon storage and greenhouse gases emission from a fluvial reservoir in an agricultural landscape. *Catena*, *94*, 53-63. https://doi.org/10.1016/j.catena.2011.03.012

Kondolf, G. M., Rubin, Z.K., and Minear, J.T., 2014, Dams on the Mekong: cumulative sediment starvation: Water Resources Research, v. 50, p. 5158-5169, doi: 10.1002/2013WR014651.

Kummu, M., Lu, X.X., Wang, J.J., and Varis, O., 2010, Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong: Geomorphology, v. 119, p. 181–197, doi: 10.1016/j.geomorph.2010.03.018.

Lehner, B., Liermann, C.R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J.C., Rödel, R., Sindorf, N., et al., 2011, High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management: Frontiers in Ecology and the Environment, v. 9, p. 494–502, doi: 10.1890/100125.

Maavara, T., Lauerwald, R., Regnier, P. and Van Capellen, P. (2017). Global perturbation of organic carbon cycling by river damming. *Nature Communications, 8,* https://doi.org/0.1038/ncomms15347

Major, J.L., East, A.E., O'Connor, J.E., Grant, G.E., Wilcox, A.C., Magirl, C.S., Collins, M.J., and Tullos., D.D., , 2017, Geomorphic Responses to Dam Removal in the United States – a Two-Decade Perspective, in Tsutsumi, D. and Laronne, eds., Gravel-Bed Rivers: Processes and Disasters: John Wiley & Sons Ltd., p. 355-383.

Minear, J.T., and Kondolf, G.M., 2009, Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California: TECHNICAL NOTE: Water Resources Research, v. 45, p. n/a-n/a, doi: 10.1029/2007WR006703.

Morris, G.L. and Fan, J., 1998, Reservoir sedimentation handbook, San Francisco: McGraw-Hill.

Nilsson, C., and Berggren, K., 2000, Alterations of Riparian Ecosystems Caused by River Regulation: Dam operations have caused global-scale ecological changes in riparian ecosystems. How to protect river environments and human needs of rivers remains one of the most important questions of our time: BioScience, v. 50, p. 783–792.

Nilsson, C., 2005, Fragmentation and Flow Regulation of the World's Large River Systems: Science, v. 308, p. 405–408, doi: 10.1126/science.1107887.

O'Connor, J.E., Duda, J.J., and Grant, G.E., 2015, One Thousand Dams Down and Counting – a Forty-Year Perspective: Science, v. 348, p. 496 – 497.

Poff, N. L. (2014). Rivers of the Anthropocene? *Frontiers in Ecology and the Environment* 12(8), https://doi.org/10.1890/1540-9295-12.8.427

Randle, T.J., Bountry, J.A., Ritchie, A., and Wille, K., 2015, Large-scale dam removal on the Elwha River, Washington, USA: Erosion of reservoir sediment: Geomorphology, v. 246, p. 709–728, doi: 10.1016/j.geomorph.2014.12.045.

Rudd, J.W.M., Hecky, R.E., Harris, R. and C.A. Kelly, 1993. Are hydroelectric reservoirs significant sources of greenhouse gases. *Ambio* 22(4), 246-248.

Snyder, N.P., Rubin, D.M., Alpers, C.N., Childs, J.R., Curtis, J.A., Flint, L.E., and Wright, S.A., 2004, Estimating accumulation rates and physical properties of sediment behind a dam: Englebright Lake, Yuba River, northern California: Water Resources Research, v. 40, p. n/a-n/a, doi: 10.1029/2004WR003279.

Snyder, N.P., Wright, S.A., Alpers, C.N., Flint, L.E., Holmes, C.W., and Rubin, D.M., 2006, Reconstructing depositional processes and history from reservoir stratigraphy: Englebright Lake, Yuba River, northern California: Journal of Geophysical Research, v. 111, doi: 10.1029/2005JF000451.

St. Louis, V.L., Kelly, C.A., Duchemin, E., Rudd, J.W.M., and Rosenberg, D.M. (2000). Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate, *Bioscience,* 50(9), 766-775. https://doi.org/10.1021/es001924p

Strand, R. I., and Pemberton, E. L. (1987). Reservoir Sedimentation." in: Design of Small Dams, 3rd Ed., Denver: Technical Service Center

Syvitski, J.P., Vörösmarty, C.J., Kettner, A.J., and Green, P., 2005, Impact of humans on the flux of terrestrial sediment to the global coastal ocean: Science, v. 308, p. 376–380.

Thonton, K.W., Kimmel, B.L., and Payne, F.E. (1990). *Reservoir Limnology: ecological perspectives*. Somerset, New Jersey: John Wiley & Sons, Inc.

Tranvik, L.J., Downing, J.A., Cotner, J.B., Loiselle, S.A., Striegl, R.G., Ballatore, T.J., Dillon, P. Finlay, K., Fortino, K., Knoll, L.B., Kortelainen, P.L., Kutser, T., Larson, S., Laurion, I., Leech, D.M., McCallister, S.L., McKnight, D.M., Melack, J.M., Overholt, E., Porter, J.A., Sobek, S., Tremblay, A., Vanni, M.J., Verschoor, A.M., von Wachenfeldt, E. and Weyhenmeyer, G.A. (2009). Lake and reservoirs as regulators of carbon cycling and climate, *Limnology and Oceanography*¸56 (6, part 2), 2298-2314. . https://doi.org/10.4319/lo.2009.54.6_part_2.2298

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P. and Syvitski, J.P.M. (2003). Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change, 39*, 169-190. https://doi.org/10.1016/S0921-8181(03)00023-7

Walling, D.E., and Fang, D., 2003, Recent trends in the suspended sediment loads of the world’s rivers: Global and Planetary Change, v. 39, p. 111–126, doi: 10.1016/S0921-8181(03)00020-1.

Waters, C.N., Zalasiewicz, J., Summerhayes, C., Barnosky, A.D., Poirier, C., Galuszka, A., Cearreta, A., Edgeworth, M., Ellis, E.C., Ellis, M., Jeandel, C., Leinfelder, R., McNeill, J.R., Richter, D.D., Steffen, W., Syvitski, J., Vidas, D., Wagreich, M., Williams, M., Zhisheng, A. Grinevald, J., Odada, R., Oreskes, N., and Wolfe, A.P. (2016). The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science, 351(6269), 137.* http://dx.doi. org/10.1126/ science.aad2622

Yang, X., and Lu, X.X., 2014, Estimate of cumulative sediment trapping by multiple reservoirs in large river basins: An example of the Yangtze River basin: Geomorphology, v. 227, p. 49–59, doi: 10.1016/j.geomorph.2014.01.014.

2 Autopsy of a Reservoir: Facies Architecture in a Multi-Dam System, Elwha River, Washington, USA

Laurel E. Stratton Garvin and Gordon E. Grant

In press, *GSA Bulletin* (as Laurel E. Stratton)

2.1 Abstract

The 2011-2014 removal of two large dams on the Elwha River, Washington State, the largest dam removal yet completed globally, created extensive cutbank exposures of reservoir sediments, allowing the first characterization of the facies architecture of sediments through direct observation in reservoirs worldwide and providing an unparalleled opportunity to assess the relationship between environmental influences, such as and changes in sediment supply, and their expression in the stratigraphic record. Using a combination of facies description from observation of 49 measured sections and >100 exposures and analysis of digital elevation models and historic aerial photographs, we delineate characteristic depositional zones of each reservoir and map the evolution of the subaerial delta over the lifespan of the reservoir. Former Lake Mills, the younger, upstream reservoir, was characterized by a tripartite, subaerial Gilbert-style delta which prograded >1 km into the main reservoir from 1927 to 2011. Sediments were composed of coarse-grained topset beds, steeply dipping foreset beds, and a fine-grained, gently dipping prodelta. While individual event horizons were discernible in fine-grained sediments of former Lake Mills, their number and spacing did not correspond to known drawdown or flood events. Former Lake Aldwell, impounded from 1913 to 2011, was initially defined by the rapid progradation of a Gilbert-style, subaerial delta prior to the upstream completion of Glines Canyon Dam. However, the 1927 closure of Glines Canyon Dam upstream caused the delta to evolve to a fine-grained, mouth-bar type delta indicative of low, finer-grained sediment. This evolution, combined with a previously-unrecognized landslide deposit into the upper delta plain, suggests that understanding the exogenic influences on reservoir sedimentation is critical to interpretation and prediction of the sedimentation within individual systems.

2.2 Introduction

As of 2018, there were an estimated 59,000 large (>15 m high) dams worldwide, intercepting 40% of total river flow volume annually, impounding an area as large as 723,000 km^2, and increasing the terrestrial water surface area by >7% (Nilsson et al., 2005; Downing et al., 2006; Lehner et al., 2011; International Commission on Dams, 2018). These dams represent humans' greatest impact on global land-ocean sediment transport, with as much as 25% of annual global sediment discharge impounded (Vörösmarty et al., 2003). In fact, despite an estimated 2300 Tg yr^{-1} increase in global sediment transport during the Anthropocene, approximately 1400 Tg yr^{-1}less sediment reaches the world's oceans (Syvitski et al., 2005).

The resulting disconnectivity in river systems and the global transfer of sediment via the "sediment cascade" has been the subject of much study. However, most work has focused on estimating the net sediment volume impact at the local, basin, or global scale (c.f. Walling and Fang, 2003; Vörösmarty et al., 2003; Syvitski et al. 2005; Kummu et al., 2010; Yang and Lu, 2014) and resulting downstream effects, both geomorphic and ecologic, of damming river systems (e.g., Nilsson and Berggren, 2000; Bunn and Arthington, 2002; Graf, 2005). The dynamics of in-reservoir sedimentation and, critically, the sediment dynamics of multiple reservoirs arranged longitudinally in a single river or watershed remain largely unexplored. As a result, our understanding of the character of sedimentation in individual reservoirs and the processes controlling them, as well as the response to changing sediment regimes in multi-dam systems, are limited.

At the scale of individual dams, most study has focused on developing approaches to aid managers in determining the local sediment yield or volumetric accumulation rate. In its comprehensive design manual Small Dams (a legacy title retained through multiple editions despite its expanded applicability to large dam design), the U.S. Bureau of Reclamation (USBR) developed a series of morphology and operations-based type curves to plot the relationship between reservoir depth and deposition. These curves recognize that sedimentation is typically weighted toward the upstream, inflow-adjacent regions of reservoirs, with the assumed delta volume equal to the volume of sand-sized or greater sediment input to the reservoir (Strand and Pemberton, 1987). The USBR considers a "typical" delta profile to be defined by distinct topset and foreset slopes separated by a pivot point located at the median reservoir operating elevation, but notes that "the prediction of delta formation is still an empirical procedure based upon observed delta deposits in existing reservoirs" and requiring extensive data collection.

The "typical" profile, as defined by the USBR, represents a Gilbert-style delta, first described in the deposits of Pleistocene Lake Bonneville (Gilbert, 1885). The Gilbert delta is a process-based paradigm, in which the decrease in slope and rapid expansion of flow abruptly decreases the competence of inflowing discharge, causing rapid, inertia-based sedimentation (Nemec, 1990a, 1990b). Accordingly, incoming sediment is deposited as a prograding foreset wedge, defined by a gravelly, subaerial topset bed, heterolithic foreset slope prograding at about the angle of repose, and downstream-fining bottomset wedge. The Gilbert paradigm has informed a vast literature of delta dynamics and remains the dominant model in lacustrine delta interpretation (e.g., Colella and Prior 1990, Talbot and Allen 1996, Reading and Collinson 1996, Wetzel 2001, Synder et al., 2006).

Examples of Gilbert-style reservoir deltas have been documented in Trinity and Englebright Lakes, two reservoirs in northern California (Spicer and Wolfe, 1987; Snyder et al. 2004, 2006). However, results from other studies of reservoir sedimentation suggest that the Gilbert paradigm is oversimplified or not applicable to many reservoirs. For example, studies in Lake Mead, located on the Colorado River and the largest reservoir in the United States, show that turbidity currents appear to be the primary mechanism of sediment transport to the stagnant-basin portions of the reservoir, modifying the shape and distribution of the delta front and transporting relatively coarse-grained sediments as far as the dam, >100 km downstream (Kostic et al. 2002, Twichell et al. 2005, Wildman et al. 2011). Additionally, research suggests that reservoirs operated for flood control, which are seasonally drawn down to create floodwater accommodation space, show patterns of sedimentation that are strongly influenced by seasonal progradation and reworking of sediment, further complicating interpretation (e.g., Ambers, 2001; Keith et al., 2016).

While endogenic (within-reservoir) dynamics can affect sedimentation patterns and sediment architecture, exogenic influences such as floods, droughts, and changes in sediment regime can be expected to similarly influence sediment transport and deltaic and lacustrine sedimentation in reservoirs downstream (c.f., e.g., Schmidt and Wilcock, 2008; Grant, 2012; Romans et al., 2016; Grant et al., 2017.) Events such as the closure of a dam upstream can be expected to influence both the volume of sediment transport and its grain size distribution, as well as to modify daily discharge, which can further influence sediment transport. For example, in Englebright Lake, a sediment- and flood control reservoir on the Yuba River in California, Snyder et al. (2004, 2006) noted a distinct transition in sedimentation rate upon the closure of a major upstream dam in the 1970s. This coring-based study, however, did not address changes in the progradation rate or style of the delta within Englebright Lake as a result of the upstream dam closure, and, with the exception of basin-scale volumetric estimates (e.g., Kondolf et al., 2014) few examples of sedimentation studies addressing cascaded reservoirs can be found.

2.3 Approach and Scope

The poorly understood dynamics of sediment deposition in reservoirs may be attributed in part to an absence of rigorous description and observation across a range of reservoir systems. Unlike natural lakes, which are well-represented within the geologic record, the architecture of reservoir sediments has thus far been relatively inaccessible to detailed study except through coring and remote sensing techniques. The accelerating pace of dam removals in the late 20th and early 21st century, however, has provided an unparalleled opportunity to examine reservoir sedimentation within a watershed context (O'Connor et al., 2015; Major et al., 2017; Foley et al., 2017). With the advent of intentional dam removal, we now have a brief window within which to examine how sediment accumulates in reservoirs before the deposit is eroded by a free-flowing river. From this, many questions become more approachable, including how multiple reservoirs interact to affect sediment deposition and what this implies for calculating reservoir accumulation rates, trap efficiencies, and lifetimes.

The 2011-2014 demolition of Elwha and Glines Canyon Dams on the Elwha River, Clallam County, Washington State, were the largest dam removals yet undertaken globally. These dams, completed in 1914 and 1927 in a watershed mostly protected from anthropogenic impacts by the basin's location in Olympic National Park, accumulated sediments for nearly a century before they were removed to restore fish passage to the upper Elwha watershed. As reservoir sediments were exposed and rapidly eroded during the dam removals, the extensive network of cutbanks and river terraces created an unparalleled, ephemeral opportunity to observe reservoir sediments *in situ*, and reconstruct some of their depositional history, with the dual goals of 1) better understanding reservoir sedimentation, architecture, and processes within a watershed context and 2) investigating how well environmental changes (e.g., floods, droughts, or changes in sediment supply) are recorded in deltaic and lacustrine environments. To approach these questions, we utilized a combination of field-based stratigraphy, historic aerial photograph analysis, and digital elevation model analysis to map the geomorphic surface features and depositional zones of former Lakes Aldwell and Mills, determine the characteristic facies associations of each zone, and analyze the morphologic styles of deltaic progradation over the course of the reservoirs' lifetime. We then use these observations to broadly interpret how reservoir cascades with multiple impoundments can control depositional styles and rates and to assess the expression of known environmental events (e.g., an 18-m reservoir drawdown in 1989 or a 50-year flood in 2007) in the stratigraphic record.

2.4 Study Area

2.4.1 Elwha River Hydrology and Geomorphology

The Elwha River watershed (833 km^2) is located on the northern Olympic Peninsula, Washington (Figure 1). Watershed elevation ranges from 2432 m in the glaciated core of the Olympic Mountains to sea level, where the Elwha River discharges to the Strait of Juan de Fuca. Most precipitation occurs from October to March, with snow dominating above ~1200 m. Precipitation is strongly controlled by elevation and ranges from more than 6,000 mm/yr on Mount Olympus to only 1,000 mm yr^{-1} at the mouth of the Elwha River; climate records (1948-2005) from the Elwha Ranger Station average 1,430 mm yr^{-1}(Duda et al., 2011).

The Elwha River is 72 km long with eight tributaries greater than third order and a total tributary length of ~161 km (Duda et al., 2008; Bromley, 2008). Annual peak discharges occur in winter, with a secondary discharge peak accompanying late spring snowmelt; the highest mean monthly discharge occurs in June and the lowest in September (Figure 2). The average daily discharge, calculated using 95 years of data, is 43 m^3s^{-1}. The flood of record occurred in 1897 (coincidentally, the first year of the historical data) at 1180 m^3s^{-1}; since then, seven measured annual peak discharges have exceeded 800 m s^{-1}, including a 50-year flood on December 3, 2007, which was the largest of the dammed era (Figure 2).

Sediment sources to the Elwha River are plentiful, due to both the history of Pleistocene glaciation in the watershed and rapid uplift rate of the Olympic Mountains. The southernmost extent of the Fraser Juan de Fuca lobe of the Cordilleran ice sheet reached approximately 13.5 km up the Elwha River ca. 14 ka, upstream (south) of Lake Aldwell but downstream (north) of Lake Mills (Long, 1975; Polenz et al., 2004; Mosher and Hewitt, 2004; McNulty, 2009). This glacial advance deposited extensive till, outwash, and glaciolacustrine formations in the lower Elwha River watershed. Upstream (south) of the continental ice extent, contemporaneous alpine glaciation advanced northward down the upper Elwha River canyon, although the extent is poorly constrained. The alpine glaciers evidently retreated before the Juan de Fuca lobe, leaving fjord-like pro-Juan de Fuca lakes that deposited glaciolacustrine sediments in the upper Mills area (Tabor, 1982; Schuster, 2005).

The bedrock in the Elwha River watershed comprises two of the major terranes on the Olympic Peninsula, a strongly deformed suite of marine sediments known as the 'Eastern Core' and an outer horseshoe-shaped belt of Eocene basaltic rocks known as the Crescent Formation (Tabor and Cady 1978). Accreted as part of Cascadian subduction, the Eastern Core is extensively faulted and has been metamorphosed to slate, schist, and phyllite, while the Crescent Formation is tilted but relatively undeformed (Tabor and Cady 1978; Tabor, 1982). The rapid uplift rate (~0.6 mm yr^{-1}; Brandon et al., 1998; Batt et al., 2001) of the Olympic Mountains produces steep slopes that slide easily and supply ample sediment to the Elwha River (Acker, 2008; McNulty, 2009; Draut et al., 2011).

While sediment sources to the Elwha are plentiful, potential erosion associated with human land use changes is relatively limited due to the protected status of much of the watershed. Eighty-three percent of the Elwha watershed is within the boundaries of Olympic National Park and a federally protected wilderness area, which was first established as the Olympic Forest Preserve in 1897. Prior to 1897, there were scattered efforts at farming, logging, and mining in the Elwha River Valley, but the density of vegetative cover and steep terrain discouraged significant development. Downstream of park boundaries, much of the lower Elwha watershed is comprised of Olympic National Forest land, where “little to no recent [logging] activity” has occurred for decades (U.S. Department of the Interior, 1996b); the remainder is private and tribal land where limited timber harvest has taken place during the 20th and early 21st centuries.

The Elwha River upstream of former Lake Mills is characterized by distinct alluvial reaches separated by bedrock canyons. The headwaters reach an average gradient of 16% and the river exhibits a convex profile (Figure 3a). Most sediment to former Lake Mills was sourced from the mainstem Elwha; however, two significant and several minor tributaries delivered sediment to the reservoir. The approximately 9-km reach between the upstream boundary of former Lake Aldwell and Glines Canyon is characterized by alluvial reaches of moderate gradient (~0.0065; Kloehn et al., 2008), separated by narrow canyons. There are few tributaries in this reach and most of these drain predominantly basaltic terrain. Only Indian Creek and a short reach of the Little River drain semi-consolidated sediments; both of these downcut through Pleistocene till for much of their lengths. With the exception of Indian Creek, which entered the head of the reservoir, sediment supply to former Lake Aldwell was limited to the mainstem Elwha River.

2.4.2 Reservoir Descriptions and Project History

Elwha and Glines Canyon Dams were completed in 1913 and 1927, respectively, to provide hydropower for development of the northern Olympic Peninsula. Elwha Dam was 33 m tall, sited to take advantage of the natural constriction of a narrow bedrock canyon on the Elwha River. It impounded former Lake Aldwell, a 1.3 km^2 reservoir comprised of two sub-basins separated by a bedrock canyon colloquially referred to as “the gooseneck.” Former Lake Aldwell had an initial water capacity of approximately $1.0x10^7$ m^3, average depth of 7.6 m, a maximum depth of 29 m, and maximum fetch of 2,000 m (Table 1). Approximately 18 km upstream, Glines Canyon Dam was 64 m tall and impounded a steep-sided, ~0.5 km-wide alluvial valley confined at the upstream end by Rica Canyon and at the downstream by Glines Canyon. Lake Mills had a similar area to Lake Aldwell, but at twice the maximum depth, had an initial water capacity approximately five times greater. During the decades of the dams’ existence, the Elwha built substantial deltas into both former reservoirs, significantly reducing their capacity, area, and average depth while increasing the shoreline complexity (Table 1, Figures 4a, 4b).

The reservoirs were operated as "run of the river" (i.e., constant head) facilities from 1975 onward (but possibly as early as the 1940s) until removal activities began, with 5.5-m drawdown experiments conducted in 1989 and 1994 and occasional drawdowns to augment downstream flows during spawning season for salmonid fish after the 2000 purchase of the dams by the National Park Service (U.S. Bureau of Reclamation, 1996a; Duda et al., 2008). Removal activities, the result of a 1996 Environmental Impact Statement which found dam removal to be the only reasonable and prudent alternative to restore the once-abundant salmonid fishery in the Elwha watershed (Duda et al., 2008; Pess et al., 2008), began in 2011.

The removal of Elwha and Glines Canyon Dams was the largest dam removal undertaken globally to date (Randle et al. 2015; Warrick et al., 2015), and required extensive study and planning. Of primary concern was developing a plan for the fate of the sediment accumulated behind the dams, the precise volume and character of which was unknown. From 1988 through 1990, a private consultant collected drill cores and bathymetric data from Lakes Aldwell and Mills to determine the volume and nature of sediments stored in the reservoir deltas (Hosey and Associates 1988, 1990a, 1990b). As part of these studies, Lake Mills was drawn down and held 5.5-m (18-ft) below normal operating elevation for four weeks in the spring of 1989. This drawdown experiment was repeated in the spring of 1994, when the reservoir was again dropped 5.5 m (18 ft) and held over a period of two weeks. The estimated total sediment volume in each reservoir calculated from the 1994 experiments (Gilbert and Link, 1995; Childers, 2000) was subsequently updated and finalized in 2010, when additional surveying was performed and a new sediment volume for Lake Mills calculated (as discussed below; Bountry et al. 2011).

On the basis of the sedimentation surveys, drawdown experiments, and additional physical modeling (Bromley et al. 2008), a sediment management plan was developed that called for phased removal of both dams over a two- to three-year period (Randle et al. 2015). Drawdown intervals were timed to balance impacts to fish and sediment erosion, with a goal to minimize the number of fish generations by reducing the overall sediment load to the Elwha River during drawdown. Accordingly, Elwha Dam was removed over the course of a single season during the winter of 2011-2012, while Glines Canyon Dam was removed in steps from late 2011 to the summer of 2014, with the loss of Lake Mills occurring in October of 2012 (Figure 5). During dam removal, the reservoirs were drained in a series of stepped drawdown events of 3 to 5 m. Each drawdown event initiated incision into the reservoir deltas, while hold periods between drawdown events allowed lateral migration, widening of the channel, and vertical drawdown. Delta progradation as the result of this stepped approach caused the deposition of up to approximately 2 to 10 m of sediment in the deep-water portions of the reservoir; however, within two years of removal initiation, 23% of the sediment in former Lake Aldwell and 37% of the sediment in former Lake Mills had been eroded (Randle et al., 2015).

2.5 Data Collection and Analysis

During the summer of 2014, the Elwha had incised to its pre-dam bed elevation through much of former Lakes Aldwell and Mills, creating extensive exposures of reservoir sediments in cutbanks where the river was actively eroding. These sediment exposures created an unprecedented opportunity to study the facies architecture of reservoir sediments through direct, spatially comprehensive observation, as opposed to remote sensing by bathymetric measurements or spot-sampling by coring.

2.5.1 Mapping and Watershed Analysis

We mapped both former reservoirs using a combination of aerial photographs, digital elevation models, thalweg profiles, and ground truthing to define depositional zones and geomorphic features in the reservoirs. Historic aerial photographs of the Lake Aldwell and Mills deltas were sourced from the United States Geological Survey's Long Term Archive at the National Center for Earth Resource Observations and Science (USGS EROS). Additional aerial orthoimagery generated based on Structure-from-Motion photogrammetry was provided by the National Park Service. Sediment deposition maps were created from digital elevation models produced by the U.S. Bureau of Reclamation (Bountry et al., 2011). All features were hand-digitized in ArcGIS applications at a scale of 1:2,000 or finer, depending on the quality of the available photographs. Areas, volumes and thalweg profiles were calculated using Spatial Analyst functions in ArcMap Version 3.7.1.

2.5.2 Stratigraphic Descriptions

We described reservoir sediments and facies architecture at over 100 locations in the former Elwha reservoirs, mapping exposures and completing 49 measured sections (Figure 4c). The location of sections was determined primarily by the accessibility and quality of exposure, and thus tended to favor recently abandoned cutbanks. In addition to those sections observed in person, we utilized photographs and samples collected by Wing (2014), to corroborate facies determinations and mapping extent. The location of sections was mapped using a survey-grade GPS and/or commercial-available unit set to collect in average mode; accuracy of both survey and commercial grade units was variable (horizontal error <3 m typical) and the steep canyon walls in upper Lake Mills occasionally prevented GPS usage. As a result, the mapped locations of stratigraphic sections were hand-adjusted using detailed orthoimagery of the reservoirs collected in July of 2014 (National Park Service, unpublished data).

On the basis of observed sections, we classified reservoir sediments into 32 distinct facies that encompass the total assemblage of sediments observed in section in the reservoirs (Table 2). The 32 facies are assigned alphanumeric codes which represent a high-level grouping according to dominant grain size (G = gravel; S = sand; HS = heterogeneous (sandy); F = fines (a field-scale determination including silt and clay); O = organic; OF = organics in fine-grained units or with a fine-grained matrix) followed by a numeric value that indicates a general fining of the dominant grain size within group (e.g., facies G1 is generally coarser-grained than facies G8 but both are dominated by gravel). We use the term facies in the descriptive rather than genetic sense and classify sediments based purely on similar grain size, sorting, and structural characteristics at the outcrop scale. Some facies (for example, those classified as "H", or heterogeneous) could arguably be considered facies associations and further subdivided. However, in making our facies designations we have tried to maintain a field-appropriate scale and thus group thin-bedded and heterogeneous, but consistent, units into single facies.

For the purposes of this study, sediments in the former Lake Mills and Lake Aldwell basins are classified into three time periods: pre-dam, reservoir, and post-dam removal. The pre-dam era represents any sediments deposited prior to dam closure in 1913 and 1927, while the post-dam removal era represents sediments remobilized by the delta progradation caused by the stepped-removal of the dams, as well as any subsequent river deposition, beginning in September of 2011. We explicitly only consider the reservoir era of sedimentation in this study (i.e., 1913 and 1927 to 2011); however, several of the 32 defined facies are the result of drawdown processes, which operated from 2011 to 2013. Where exposed, the contact between pre-dam and reservoir sediments is typically clear; the sedimentation resulting from dam removal activities, however, can be more challenging to distinguish and could not always be conclusively determined. Discussion of the pre-dam and post-dam removal sediments, as well as more detailed criteria for facies characterization, is included in the supplementary materials.

2.5.3 Sedimentation Rates and Reservoir Accumulation Volumes

Immediately prior to dam removal, Bountry et al. (2011) estimated that former Lake Mills stored 15.6 (±2.7) x10^6 m^3 of sediment, 51% of which was in the delta, 38% on the reservoir floor and margins, and 11% in the Rica, Boulder Creek, and Cat Creek canyons. This estimate for former Lake Mills was produced by comparing a survey completed in 2010, a survey completed in 1994 (Gilbert and Link, 1995), and a topographic map completed prior to the closure of Glines Canyon Dam; in it, Bountry et al. (2011) noted that sedimentation rate from 1994 to 2010 was approximately 47% greater than from 1927 to 1994, an effect probably attributable to landslide activity in the upper watershed. Initial estimates of sediment storage in former Lake Mills appear to have been accurate within the margin of error; following dam removal, Randle et al. (2015) revised the total sediment accumulation in former Lake Mills to 16.1 (±2.4) x10^6 m^3 based on better pre-dam control following dam removal.

Based on the estimated sediment volume in former Lake Mills discussed above (Bountry et al., 2011; Randle et al., 2015), an estimated trap efficiency in former Lake Mills of 0.86 (Childers et al., 2000), and sediment load calculations from data collected during water years 1995-1998 and 2006-2007 (Curran et al. 2009), the average sediment yield of the Elwha watershed above former Lake Mills is estimated between 1.84×10^5 m^3yr^{-1} and 2.26×10^5 m^3yr^{-1}. However, based on accumulation rates from 1994 to 2010, this rate may be as high as 3.60 0^5 m^3yr^{-1} (after Bountry et al., 2011).

Calculation of sediment yield below former Lake Mills and accumulation rates in former Lake Aldwell is significantly more complicated. No data to calculate the sediment yield for the Elwha River above former Lake Aldwell was collected before the 1927 construction of Glines Canyon dam or before its removal in 2012. Additionally, no formal topographic survey of site of former Lake Aldwell was completed prior to the completion of Elwha Dam in 1913. As a result, estimates of sediment yield and accumulation rates are based exclusively on in-reservoir bathymetric surveys from 1994, 2010, and 2012-2014 (after dam removal) and interpolation of the pre-dam valley floor. Prior to dam removal, the sediment volume in former Lake Aldwell was estimated as ~2.97 (±1.0) $x10^6$ m^3 (Gilbert and Link, 1995; Bountry et al., 2011). Based on additional evidence following dam removal, this estimate was revised to 4.9 (±1.4) $x10^6$ m^3 (Randle et al., 2015). We discuss this discrepancy using our stratigraphic interpretations and the process-based insight gleaned therein in Section 5 (Discussion), below.

2.6 Results: Depositional Characteristics of the Former Reservoirs

Here, we characterize the sedimentation in former Lakes Mills and Aldwell according to the geomorphology of reservoir sediments at the time of dam removal, the style and rate of delta progradation over the lifespan of the former reservoir, and the facies architecture of depositional environments within each reservoir.

2.6.1 Lake Mills

2.6.1.1 ***Geomorphology***

At the time of removal, the Lake Mills delta was characterized by a subhorizontal delta plain extending nearly 1 km into the main body of the reservoir, with accumulation of coarse-grained sediments nearly 2,000 m upstream into Rica Canyon (Figure 4b). The delta geometry was characterized by a sharp break in slope (“pivot point,” as typically referred to in reservoir literature; e.g., Morris and Fan, 1997) with average delta slope gradient of 0.30. Beyond the delta slope, sediment accumulation formed a wedge of sediment thinning toward the main lacustrine basin. Beyond the influence of deltaic sedimentation, the thin sediment accumulation approximately paralleled the pre-dam gradient (Figure 3b).

As mapped in Figure 6a, the former Lake Mills reservoir consists of six depositional regions: the basin (i.e., lacustrine area), prodelta, delta slope, delta top, delta plain, and associated hillslope areas. Key geomorphic features within these regions (mapped only where visible in orthoimage or field mapping) include subaerial and subaqueous bars, vegetated regions of the delta plain, and accumulations of woody debris.

At about the time of dam removal, the Lake Mills delta plain was characterized by a well-vegetated, alluvial upper reach and cuspate delta mouth. Deposition in Rica Canyon was characterized by extensive alternate bars, while the Cat Creek canyon was completely vegetated, with multi-threaded stream channels extending to the main Mills delta plain. Immediately downstream of the mouth of Rica Canyon, where the main Lake Mills basin expanded, the mainstem Elwha was split by a central "middle ground" bar (*sensu* Wright et al., 1977) heavily armored with woody debris. The upper delta plain formed an anastomosing floodplain, characterized by thickly vegetated bars, extensive subaerial bars, and stable, multi-threaded channels with minor distributary splays. The lower delta plain was characterized by more complex morphology, with complexly interfingered subaqueous and subaerial bars. Progressive accumulation of woody debris and consequent armoring of channel banks appears to have deflected the main distributary channel to the left bank (west), forming a single deep channel that distributed the majority of the incoming Elwha discharge to the active delta mouth.

The majority of the delta front was characterized by a cuspate margin well-armored by woody debris. At the time of dam removal, the main delta had prograded as far as Boulder Creek, a major, steep tributary with significant secondary delta accumulation. The Boulder Creek delta, protected by an upstream hillslope knob protruding into the main body of the reservoir, formed a lobate, Gilbert delta with a slope of 0.30. Where the Boulder Creek delta interacted with the main delta, the delta top (defined here as the subaqueous portion of the delta plain; i.e., subaqueous deposition upstream of the pivot point) was characterized by a shallow, subaqueous middle bar extending well beyond the cuspate delta margin. The mean gradient of the delta slope beyond this subaqueous mouth bar was considerably less than the main delta, at only ~0.18.

Downstream of the delta front, detailed geomorphic characteristics of the subaqueous regions (basin, prodelta, delta slope) were difficult to resolve at the scale of available bathymetric data. The prodelta wedge was characterized by low-angle low-gradient (average 0.02) deposits and lacustrine sedimentation reflecting a subdued form of the pre-dam topography.

2.6.1.2 Delta Evolution

We characterized the evolution of the delta and character of delta deposits in former Lake Mills using historic aerial photographs of the Lake Mills region. The earliest aerial imagery of Lake Mills was taken in 1939, when the reservoir had been impounded for only 12 years and showed an irregularly lobate, subaerial delta extending approximately 225 m down the Cat Creek canyon (Figure 7). By 1956, the Cat Creek delta appears to have prograded approximately 0.37 km into the main reservoir with ample accumulated sediment. The imagery shows the reservoir elevation below full pool indicating at least occasional drawdown events. Still, by 1976 (after 49 years of operation) no subaerial delta had yet established itself in the main reservoir. By 1981 (not pictured), aerial imagery shows a shallow subaqueous, cuspate delta with cuspate delta mouth extending nearly 700 m into the main Lake Mills. The upper 400 m appears to have been at least partially subaerial, forming an irregular system of bars. The Boulder Creek delta appears to have been well established: while not subaerial, a distinct lobate form is visible.

Delta morphology appears to have been significantly altered by the drawdown experiment of 1989, which dropped and held the water surface elevation of Lake Mills at 5.5 m below normal operating elevation for four weeks in the spring of 1989 (Childers et al., 2000). This prolonged drop in base levels appears to have caused major erosion of the delta plain. Rather than an arcuate, well-defined delta mouth as shown in the 1981 aerial photograph, the delta was characterized, in September 1990, by side bars in the lower delta plain and a major mid-channel bar at the upstream head of the basin (Figure 7). The central delta front appeared to be rebuilding in the form of multi-storied lobes of sediment prograding toward the original delta mouth. Significant woody debris appears to have accumulated at the head of the mid-channel bar and on the sidebars.

By 2004 (following an additional drawdown experiment in 1994), the Elwha had re-established a fluvially-dominated delta plain that appears to have remained relatively stable until removal activities began in 2010. However, the active mouth bar near the mouth of Boulder Canyon (as described above) appears to have evolved from a lunate form in 2006 to the mid-channel bar observed in 2009.

2.6.1.3 Facies Associations

Distinct facies were identified in the two Elwha reservoirs (Table 2). When mapped by depositional region, these facies are observed to occur in distinct groupings according to depositional area, as shown by the representative sections (Figure 8). The patterns observed in these representative sections, as well as from those locations mapped in Figure 4C, can then be used to create a series of idealized stratigraphic sections for former Lake Mills (Figure 9) and a conceptual model of sedimentation (Figure 10a). Working generally from upstream to downstream, these characteristic facies associations, as defined for former Lake Mills, are discussed below. Alphanumeric designations are keyed to stratigraphic sections as described above (Table 2).

2.6.1.3.1 Delta Plain (G1, G5, S1, O1, F6)

As the result of the stepped drawdown approach to dam removal discussed above (Figure 5a; Randle et al., 2015), preservation and exposure of the former Lake Mills delta plain was limited. While supplemented with photographs from Childers et al. (2000) and unpublished photographs from the National Park Service, interpretations in former Lake Mills are thus heavily biased toward marginal sediments, which were characterized by stable, primary distributary channels over most of the evolution of the delta plain (Figure 7). Marginal upper delta plain deposits are characterized by cobble to boulder gravels occurring as multi-story sheet deposits, interbedded with pebble foreset and plane-bedded sand units (G5, S1; Figures 8, 9A, 9B). Beds are >1 m thick and massive to crudely stratified; where present, the matrix consists of sand and pebbles, with little silt present. Lenses of clast-supported to open framework branches are common (O1).

However, better preservation in portions of the delta plain in Boulder Creek, a similarly steep-gradient, Gilbert-style delta, indicates that topset units were primarily composed of coarse gravels with occasional interbedded sand and organic units. Finer-grained facies, like OF1 and F6, composed of interbedded, subhorizontal silt and sand units with or without prominent organics, are present but appear to occur only as thin veneers over the topset gravel beds. These facies appear to have been deposited in the inactive portions of the delta plain, allowing the establishment of stable vegetation.

2.6.1.3.2 Delta Top (O3, G4, S1)

At the time of dam removal, the active, subaqueous Lake Mills delta top was characterized by a lobate middle ground bar prograding over the Boulder Creek prodelta (Figures 6A, 8). Exposure in this region was poor by the summer of 2014, but stratigraphic sections show O1 and HS2 foreset beds underlying delta mouth bar facies O3, G4, and S1. Unit G4 consists of silty sandy gravel to sandy gravel, characterized by sheet-like geometry and medium gravel lag. It occurs as multi-story units and may or may not be interbedded with other facies. Where observed in Lake Mills, it tends to be interbedded with HS1, a poorly sorted sand and pebble unit characterized by thick (1 m) accumulations of clast-supported organic debris. The organic debris tends to occur as lenses indicating channel lag or as lateral accretion cross beds in preserved channel forms.

2.6.1.3.3 Delta slope (S3, O1, O2, G3, G6, G10, HS2, HS3)

Downstream of the delta top ‘pivot point’, the delta slope in Lake Mills was characterized by steeply dipping (~30°) foreset beds with variable lithology and a sharp to tangential toeset (Figures 3B, 8). No well-exposed beds were preserved in the main body of the reservoir; however, anecdotes and photographs from the 1994 drawdown experiment (Childers et al., 2000) recorded extensive, steeply dipping foresets that were progressively exposed as the delta adjusted to a lower base level. In the Boulder Creek delta, steep foresets consisting of Facies G6, HS3, and O2 were well-preserved (Figure 8). Facies HS3 and O2 are similar to HS2 and O1 but steeply dipping. O2 represents detrital organic accumulations up to 1 m thick, extending the length of the foreset bed. Toward the mouth of Boulder Canyon, toeset deposits were absent and foreset beds were observed in sharp contrast with underlying, fine-grained deposits. More distally, where the Boulder Creek delta prograded to interact with prodelta deposits of the main Mills delta, foreset beds were observed to grade sigmoidally to finer-grained facies, forming extensive toeset deposits.

Toeset facies (gradational with the proximal prodelta facies) include S3, G10, F1, O1, and HS2 (Figure 9A). These facies tend to be variably interbedded and to decrease in gradient down-section. Complexly interbedded with S3, O1, and HS2, (all finer-grained facies, discussed further below) the G10 facies is composed of a low-angle sand to granule and pebble conglomerate. It tends to be well sorted and thickly bedded (average 0.5 to 1 m), pinching out downstream. Similarly interbedded but irregularly occurring, the O1 facies consists of coarse, abraded organic detritus forming lenses and beds that pinch out downstream. These organic units tend to be interbedded with medium to coarse sands, but may occur independently and tend to have limited matrix. In the upper portion of the toeset facies, interbedded fine sand and silt represent a lower-energy regime. Facies HS2 tends to be complexly bedded and to exhibit wave ripples to wavy bedding. G3, an angular, matrix-supported deposit we interpret as evidence of a debris flow extending into toeset section (Table 2), is not representative of delta processes and is discussed below.

2.6.1.3.4 Prodelta (F2, F1, S3)

The prodelta in former Lake Mills was dominated by the sand-dominated facies S3 grading to the fine-grained F1 and F2 deposits with distance from the influence of deltaic processes.

Proximal (Bottomset) Close to the delta face, coarse-grained toeset facies decrease and grade to S3 (Figure 9A), a longitudinally- and laterally-extensive deposit of well-sorted fine- to medium sand with little to no silt matrix and interlaminated to interbedded fine, medium, and coarse organics. Planar to sigmoidally shaped cross-laminated beds occur from 20 cm to ~1 m as stacked beds with broad lateral undulations. Climbing ripples are common. Bark fragments, conifer needles, and twigs with intact bark occur as beds up to 10 cm thick proximal to the delta, 5 cm thick in the distal prodelta, and in the lee of climbing ripples. Closer to the delta, beds of the S3 facies are laterally extensive for tens for meters and are characterized by broad undulations and a variable but low-angle gradient of ~0.01.

Distal With distance from the delta, the S3 facies thin and grade to the F1 facies, which consists of mudstone to silty sand closely interbedded with fine to medium sand beds, forming a 'striped mudstone' (Table 2; Figures 9A, 9C). Sand beds in the F1 facies average approximately 5 cm thick and consist of fine- to medium sand typically preserved as discrete current ripple formsets. At their maximum, sand beds may reach 15 cm thickness with prominent cross- and planar bedding, often highlighted by conifer needles preserved in the ripple lee. Both the thickness and frequency of well-sorted sand beds decrease down-section; eventually grading to Facies F2. These units consist of subhorizontal, interlaminated to interbedded muds and silty fine sand with well-sorted fine sand interbeds at irregular intervals. Subtle draping of pre-existing topography is occasionally visible but tends to be muted by the lakebed facies that it overlies (discussed below). Sandy interbeds are uncommon but not rare, occurring as single, discrete formsets of current ripples or as beds of subcritical climbing ripples to ~10 cm thickness. F2 deposits are infrequently interrupted by chaotic lenses or channelized units of coarse organics consisting of sticks, bark fragments, cones, and needles in a matrix of poorly sorted silty sands.

In Lake Mills, the F1 facies is extensive and thick, forming the majority of >5 m thick sections exposed throughout the prodelta area. The F1 facies appears to be dominant compared to F2, which is marginal in thickness and occurrence; however, the relative scarcity of F2 may reflect poor preservation in the distal prodelta. An erosional scallop exposing an east-west face of prodelta sediments shows F2 deposits along the reservoir margins, which grade to F1 facies both above and laterally toward the depositional axis of the reservoir basin.

2.6.1.3.5 Basin (F4, F2)

Downstream of the distal prodelta, basin deposits in former Lake Mills grade from F1/F2 to the F4 faces, which are thick, laterally extensive, and homogeneous. The

F4 facies are composed of silty deposits with mm- to cm-scale, subhorizontal laminations. Interlamina composed of very fine sand or degraded organic detritus are present but uncommon. Lower F4 sediments tend to drape underlying pre-dam features (including both topography and old growth stumps left in place at the time of reservoir filling). With thickness, however, this draping becomes muted, and the majority of F4 and F2 sediments are subhorizontal. In section, basin sediments are distinctive due to a tendency to form competent bluffs that weather in blocky or conchoidal fracture patterns. Incomplete sections composed entirely of the F4 facies were observed in excess of 5 m thick approximately 400 m upstream of Glines Canyon Dam, while immediately downstream of the mouth of Rica Canyon, F4 was observed with a maximum thickness of <0.5 m. While generally homogeneous across their full thickness, the F4 facies is occasionally interrupted by laterally-extensive interbeds of the F1 facies, which may extend well into the distal portions of the reservoir (close to the dam).

2.6.1.4 Colluvial and shoreline deposits

In most areas, the reservoir margins are characterized by steep, submerged former hillslopes (Figure 4C). Deposition on the reservoir margins appears to be net accretionary (as opposed to erosional, as is common in reservoirs operated with large seasonal drawdowns). In most areas, deposition reflected the characteristics of the broader depositional zone (i.e., F4 in basin margins, G1 in upper delta plain margins) but tended to be thinner and to follow the angle of the hillslope. In shallow-water margins influenced by deltaic sedimentation, stumps and standing trees remaining from the pre-dam era formed barriers to flow, resulting in complex imbrication patterns and fine-grained sedimentation in their immediate lea. In the upper portion of former Lake Mills, aerial photographs and Facies G3 show evidence of non-fluvial sediment transport to the reservoir. Un-vegetated, sharp scarps in Pleistocene outwash and lacustrine deposits in the hillslopes above former Lake Mills (Figure 7) suggest some influx due to mass wasting, while the angular G3 facies indicates that incursions of hillslope material contributed at least minor sediment volume to the reservoir.

2.6.1.4.1 Cat Creek delta (G10, G8, HS3, F6, OF2, F3)

The only complete sections observed in former Lake Mills, as well as the only interdistributary portions of the delta plain, are preserved in the Cat Creek delta (Figure 9c), located immediately downstream of the main Rica Canyon inflow to the reservoir. Basinal and prodelta deposits are characterized by the F2 and F1 facies, as in the main Lake Mills basin (Figure 9A). Similarly, the toeset deposits are characterized by the G10 and HS1 facies. However, as compared to Lake Mills, the foreset facies in Cat Creek are less steeply dipping and finer grained (G7, HS3). Active topset channels are characterized by coarse gravels, but interdistributary areas are characterized by well sorted gravels, cross-bedded gravels (G8), massive clay (F3), coarse organic detritus in a clay matrix (OF2), and interbedded silt and poorly sorted sand (F6).

2.6.2 Lake Aldwell

2.6.2.1 Geomorphology

In the years immediately prior to dam removal, upper Lake Aldwell was characterized by a low-gradient, irregularly-shaped shoal-water or slope-type delta, defined by a subhorizontal subaerial delta plain and shallow, subaqueous delta front (average gradient 0.04) separated from a low-gradient (average gradient 0.03) prodelta wedge by a moderate gradient delta slope (average gradient 0.08) (Figures 5b and 6b). The lacustrine portion of the basin was characterized by thin accumulations of sediment with similar gradients to the pre-dam topography, while the constriction separating the main basins appears to have had little sediment deposition.

We subdivided and mapped the former Lake Aldwell basin into six depositional areas, similar to former Lake Mills (Figure 6b). However, Lake Aldwell did not have a distinct pivot point as described in Lake Mills, but was characterized by a low gradient, subaqueous delta top and a broad delta slope defined by the lee angle of major mouth bars. This delta slope was gradational in nature and, as discussed below, was not characterized by foreset beds, as in Lake Mills. In addition to those geomorphic features mapped in former Lake Mills, distinctive features in former Lake Aldwell include prominent mouth bars and mass wasting deposits.

In the years immediately prior to dam removal, most of the upper delta plain was vegetated by mature broadleaf trees. A subtle but distinct break in crown height along the western margin of the delta plain is evidence of a landslide deposit (Figure 11; discussed below). Additional, immaturely vegetated areas point to the development of incipiently stable conditions over the lifespan of the reservoir. Alluvial areas within the delta plain were characterized by a primary active channel with multiple partially abandoned distributary channels. By 2009, the main fluvial channel extended nearly a kilometer into the reservoir with little sinuosity; it was marked by subaqueous levees and crevasse splays on the northern bank toward the delta front. As in Lake Mills, subaerial or incipiently subaqueous bars were commonly ‘armored’ by accumulations of large woody debris at the head (Figure 6b).

In the lower reaches of the delta plain, crevasse splays from the main fluvial channel coalesced into a broad, irregularly-shaped delta front (Figure 6b). Where the main fluvial channel opened into the Aldwell basin, a series of lunate mouth bars prograded beyond the intermittently active portion of the delta front. The active portion of the delta appears to have been prograding along its western margin, where Indian Creek, which entered the reservoir near its head but was channelized along the western margin of the reservoir for nearly a kilometer, opened to the main delta. Muted lunate sedimentation patterns visible on the DEM indicate that mouth-bar progradation was previously active along the eastern margins of the reservoir.

Downstream of the deltaic deposits, Lake Aldwell was characterized by a prodelta wedge with average gradient of 0.03 that appears to have prograded primarily along the western margin of the reservoir. Beyond the prodelta wedge, reservoir sedimentation is reflective of lacustrine, suspension fallout processes, with sedimentation mirroring and muting pre-dam topography. In areas, the pre-dam channel thalweg was clearly visible. Sedimentation in the constricted ‘gooseneck’ portion of Lake Aldwell was very low; the lower basin of Lake Aldwell shows evidence of lacustrine sedimentation and creeping slump block movement. Similar to former Lake Mills, the reservoir margins appear to have been net accretionary.

2.6.2.2 Delta Evolution

The earliest available depiction of the Lake Aldwell basin is a 1919 topographic map (surveyed 1917-1918, <5 years after dam closure), in which no subaerial deltaic exposure was indicated (Figure 7). By 1939 (~25 years after dam closure and 12 years after the upstream closure of Glines Canyon Dam), a subaerial delta had prograded nearly 650 m into Lake Aldwell. The 640-m main channel appears to be artificially straight and shows cross-cutting relationships with transverse channels and vegetation growth in the lower delta, suggesting that the reservoir delta had been dredged to establish a channel into the main body of the reservoir and away from significant, abandoned channels along the western and eastern margins of the main Aldwell basin. Much of the delta appeared to be well-vegetated, indicating that by 1939 it had already been stable and subaerial for some time. The delta appears to have been active primarily along the northwestern front, where sediment from both the mainstem Elwha and Indian Creek, which enters the reservoir ~400 m west of the 101 bridge but was channelized against the western basin margin, entered the main body of the reservoir. In contrast to later years, the delta slope appears to have been well defined.

From 1939 to 1956, the subaerial delta extent appears not to have changed appreciably. The previously exposed subaerial bars were densely vegetated by 1956, however, and the river appears to have reoccupied the channel along the eastern basin margin, depositing the reworked sediment further into the deltaic margins. By 1976, the eastern subaerial deltaic margin had prograded nearly 400 m from the point of divergence with the main channel, while a lunate, subaqueous bar was evident beyond. Mass wasting deposits from two scarps in the western hillslope nearly filled the western portion of the upper basin sometime before 1976 (Figures 11B, 11C); given the re-establishment of the Indian Creek delta channel and the prominent vegetation on both scarp and landslide runout, this slide probably occurred relatively soon after the 1956 aerial photograph was taken. Probably as the result of this new source of sediment, the elongate central bar of the main delta had prograded an additional ~250 m into the reservoir, with well-developed subaqueous central levees and mouth bars beyond.

From 1990 to 2009, the Lake Aldwell subaerial delta did not prograde appreciably, but the Elwha River continued to rework the uppermost delta plain, nearly abandoning the original and easternmost channels to shallow water backwaters and reworking portions of the vegetated delta plain. Riffles evident in a 2006 aerial photograph show that avulsion was active during this time; by 2008 and 2009, the river had established a relatively broad, main channel to the active delta front.

While the subaerial portion of the delta remained relatively inactive from 1976 onward, the subaqueous delta front evolved considerably. Prior to 1976, the delta front appears to have been well-defined, with a distinct delta slope and well-defined, lobate mouth bars (Figure 7). After 1976, the delta developed an extensive shallow subaqueous front, with pro-delta lunate bars extending well into the basin. By 2009, as discussed above, the main delta distributary channel was characterized by mid-channel and lateral levees, with extensive crevasse splays forming a subaqueous delta front composed of welded mouth bars.

2.6.2.3 Facies Associations

As in former Lake Mills, described stratigraphic sections in former Lake Aldwell were mapped and assigned to facies associations to create a composite stratigraphic column of the facies architecture of the reservoir (Figure 12). These descriptions utilize the same facies codes and descriptions as former Lake Mills (Table 2), but combine to form unique characteristic associations (Figure 13). These facies associations, discussed according to depositional zone and illustrated by a conceptual model (Figure 10B), are discussed below.

2.6.2.3.1 Delta Plain (G2, G4, G8, G9, F3, F6, S1, O1, OF1)

The delta plain in former Lake Aldwell was characterized by a variety of alluvial and deltaic environments, leading to diverse facies deposition (Figures 12, 13). At the time of removal, much of the upper delta plain was emergent and had been stably vegetated for decades, forming a variety of side channels, overbank areas, and quiescent interdistributary areas (Figure 6B). This environment most closely approximates an alluvial flood plain and is characterized by well sorted channel sands and gravels (G9, S1), clay beds (F3, O1), and interbedded fine sand, silt and organics in crevasse splays

(OF1). The upper alluvial channels, grading to delta distributary channels, are characterized by extensive, massive to weakly stratified sheets of coarse gravels (G2, G4), which appear to have been relatively limited in extent, as further discussed below.

Given the relatively low gradient of the uppermost Aldwell basin (Figure 3C), the massive old-growth stumps logged and left in place during dam construction protruded into the shallow-water delta plain sediments (Figure 11A). These appear to have created localized pockets of complex sedimentation immediately downstream but not to have broadly influenced sedimentation in the delta plain. Exceptions to this appear to have been where stumps served as a focal point for rafts of woody debris to accumulate; in several instances, subaerial delta bars armored by woody debris appear to have been anchored by these old growth, rooted stumps.

2.6.2.3.2 Delta Top (O3, F5, HS1, S1, S2, G8)

In contrast to former Lake Mills, the active delta mouth in former Lake Aldwell was characterized by broad distributary channels leading to a large, shallow subaqueous area (Figure 6). Where preserved, the delta mouth bars form broad, overlapping channels eroded into the delta slope sands, below (Figure 13B). These channels preserve significant accumulations of clast-supported woody debris in a sandy matrix (O3), which occurs as channel lag or forms lateral accretion surfaces. Thick accumulations of the F5 facies, a muddy unit finely interlaminated with well-preserved broadleaf lamina and well-preserved wave ripples, occur in interdistributary areas.

Where the mouth bars merge to form a low-gradient sandy delta top, the HS1 and S1 facies, characterized by coarse sand and accumulations of coarse woody debris in poorly sorted, sheet-like geometry, are common. Facies HS1 is characteristic of the dam removal flood deposits in both reservoirs, but occurs broadly as a primary depositional unit in the delta top of former Lake Aldwell. Its occurrence is somewhat puzzling, but may represent similar processes to those that created the F1 facies in former Lake Mills, i.e., the alternation between event-flow deposits and background, suspended sediment deposition. In section, the unit appears chaotic due to the disruption of woody debris, but is actually well-sorted. Where present in primary reservoir deposits, the absence of fine-grained material suggests that the HS1 facies is caused by winter flood deposition to the delta top, then winnowed by summertime distributary flows to the delta top combined with the disturbance of wave action.

Upstream of the delta mouth bars, the preserved, distal distributary channels are characterized by the S2 facies, which is composed of interbedded medium to coarse sand that is typically capped by laminated organics and silt to form multi-storied couplets (Figures 11A, 11B). Near the uppermost head of the reservoir, the S2 facies coarsens to form thick (~0.5 m) beds of fine, well-sorted gravels interbedded with silts and organics (G8).

2.6.2.3.3 Delta Slope (S3, HS2, G7)

In contrast to Lake Mills, the active delta slope in former Lake Aldwell was not part of a tripartite topset-foreset-bottomset morphology; instead, the delta slope tended to be characterized by mouth bar sands (S3) without a distinct break in slope (Figures 6, 10). The S3 facies is similar on a local scale to former Lake Mills, but tends to be both thinner bedded and less extensive (or absent). In longitudinal section, it does not display the same prominent undulations as in Lake Mills but tends to form relatively uniform, low-gradient beds demarcated by climbing ripples or plane bedding. In lateral section, minor silt beds form subtle lenses. Overlying or instead of S3, the HS2 facies is characterized by thinly-bedded, well-sorted sand and silt couplets, which often exhibit wavy bedding.

Coarse-grained foreset beds are not entirely absent in former Lake Aldwell, however. While gravels are absent in the portion of the delta slope that was active at the time of dam removal, in the upper reservoir, matrix-rich gravels forming distinct foreset beds (G7) and horizontal topsets were exposed along the reservoir margin (Figure 14). The G7 facies in former Lake Aldwell has a lower angle than similar deposits in former Lake Mills, and appears to have prograded directly over F2/F4 basin sediments (in contrast to the expansive prodelta sands of former Lake Mills). At the time of dam removal, the overlying topset beds were nearly subaerial.

2.6.2.3.4 Prodelta (F4, F2)

Prodelta deposits in Lake Aldwell are similar to the more distal portions of the prodelta in former Lake Mills but lack the extensive deposits of the F1 facies in that reservoir. Lakebed deposits fine both down-section and downstream, typically grading from F2, distal prodelta deposits, to fine-grained lacustrine-style deposits (F4; discussed below; Figure 12). The F2 units consist of subhorizontal, interlaminated to interbedded muds and silty fine sand with well-sorted fine sand interbeds at irregular intervals. Subtle draping of pre-existing topography may be visible but tends to be muted by the underlying lakebed facies. Sandy interbeds are irregular but not rare, occurring as single, discrete formsets of current ripples or as beds of subcritical climbing ripples to ~10 cm thickness. F2 deposits are infrequently interrupted by chaotic lenses or channelized units of coarse organics consisting of sticks, bark fragments, cones, and needles in a matrix of poorly sorted silty sands. In former Lake Aldwell, packages of F2 overlying F4 were observed as thick as 3.5 m, with an erosional upper contact.

2.6.2.3.5 Basin (Lakebed) Deposits (F4)

Basin deposits in Lake Aldwell are extensive and homogeneous, consisting primarily of the F4 facies. Closer to the delta, they tend to consist of silty deposits with mm- to cm-scale, subhorizontal laminations and occasional very fine sand or degraded organic interlaminae, while the lowermost and/or distal basin deposits tend to be clayey (Figure 12), with a distinct blue-gray hue. Lowermost F4 sediments drape pre-existing topography at both the individual cobble and section scale, though the draping effect is eventually muted by continued sedimentation. F4 sediments are subhorizontal and laterally contiguous for tens of meters, with a tendency to weather as competent bluffs with blocky to conchoidal fracture patterns. In Lake Aldwell, F4 deposits were observed as thick as 2.5 m with an erosional upper surface, thinning to about 1.3 m of complete section immediately above the gooseneck.

2.6.2.3.6 Colluvial and shoreline deposits

Mass wasting appears to have played a significant role in the sedimentation of Lake Aldwell (Figures 11B, 11C), as is discussed in detail below. However, no mass wasting deposits were exposed for characterization of the facies. Similar to former Lake Mills, the former Lake Aldwell shorelines were characterized by thin, draping deposits of F4 and F2, or by a variety of coarse-grained delta plain facies. Many trees growing along shoreline at the time of reservoir inundation persisted throughout the reservoir lifespan; these appear to have influenced sedimentation significantly by serving as initiation points for rafts of organic debris to accumulate, creating areas of complex hydraulics and sedimentation (similar to the effect in the delta plain discussed above; see stumps in Figures 11A or 14 for examples).

2.7 Discussion

The architecture, geomorphology, and evolutionary sequences in the two reservoirs record both their underlying depositional processes and the distinctive environmental histories of the two reservoirs. Here we consider how depositional processes, as revealed by stratigraphy, varied between the reservoirs and implications for interpreting sequences of reservoir deposits in rivers having multiple dams. Because the entire lifespan of both reservoirs existed within the historical record (as opposed to natural lakes), these environments provide a unique record with which to assess the connection between exogenic events and their stratigraphic expression, creating the potential for great insight into interpretation of paleoenvironments and the preservation of environmental events in the deep stratigraphic record.

2.7.1 Lake Mills

The morphology and sedimentation patterns in former Lake Mills closely approximate an ideal coarsening-upward Gilbert sequence, defined by a tripartite structure consisting of coarse-grained, subhorizontal topset beds, steeply dipping foreset beds, and a downstream-fining bottomset wedge (Figure 10A). The close correlation between the sedimentation patterns observed in former Lake Mills and those of the ideal Gilbert-style delta indicate that the processes operating to deliver and deposit sediment in the reservoir are well-described by the lacustrine-based Gilbert paradigm and are in keeping with the “typical” reservoir profile described by the USBR (Strand and Pemberton, 1987). However, the heterogeneity of deltaic slope deposits in the Boulder Creek delta, the importance of the F1 “striped mudstone” facies in the prodelta, and the occurrence of sandy interbeds in the lacustrine basin, all suggest additional complexity in the processes influencing downslope transport in former Lake Mills.

Progradation in Gilbert deltas typically occurs by a variety of avalanching processes down the delta slope, ranging from continuous transport of sediment over the delta front to mass movement in response to oversteepening or flood events (Nemec, 1990b). The range of avalanching processes tends to produce relatively heterolithic assemblages controlled by and traceable to individual storm or flood events (Ambers 2001; Pondell and Canuel, 2017). This morphology is reproduced well in the delta slope region of former Lake Mills (Figures 8, 9A), with low-angle interbedded fine gravels, coarse organics, and sands (G10, O1, S3, and HS2) overlain by steeply dipping sand, organic, and coarse gravel beds (O2, HS3, and G6), and coarse gravel, subhorizontal topset beds (Facies G1, S1, G5, and O1) to form the typical heterolithic, tripartite Gilbert delta.

Beyond the delta slope, the occurrence of coarser-grained material in the deep water, suspended sediment-dominated portions of lakes and reservoirs is typically attributed to storm-triggered turbidity currents, which have been extensively documented in lakes and reservoirs (e.g., Forel 1892; Sturm and Matter, 1978; Giovanoli, 1990; Nemec, 1990b, Kostic, 2002; Twichell et al., 2005). Resistance to mixing created by the density difference between non-turbid lake waters and sediment-laden density flows allow turbidity currents to maintain flow competence for great distances into stagnant basins (c.f. Thornton et al., 1990). These flows tend to deposit characteristic turbidite deposits, in which fining-upward graded beds record deposition from peak flow to the waning limb of the event (Reading and Collinson, 1996).

However, little evidence of graded bedding was observed in former Lake Mills. Instead, the proximal prodelta was dominated by the F1 “striped mudstone” facies (Figure 9A), consisting of laminated silts regularly interbedded with well-sorted sandy interbeds characterized by single cosets of climbing ripples or by rhythmic, isolated formsets of current ripples. We interpret this facies as the result of density flows, but suggest that it may be the result temperature-derived plunging flow instead of a flood-derived turbidity current. The Elwha River experiences a major discharge peak during the summer resulting from melting of the heavy snowpack in its high-elevation headwaters (Figure 2). These summer high flows remain very cold, in contrast to the warm surface temperatures of the stratified reservoir waters, creating a temperature-derived resistance to mixing and causing river inflows to flow for great distances along the reservoir bottom before mixing with the reservoir hypolimnion (Thornton et al., 1990; Munn et al., 1998).

We suggest that temperature-derived plunging flows provide a mechanism to sort and redistribute sands and silts from the delta slope into the distal prodelta, well beyond the occurrence of sand predicted by the Gilbert model of sedimentation.

This observation is in keeping with Snyder et al. (2006), who noted that the ideal progradation of the simple Gilbert delta is in reality rather rare. In former Lake Mills, as the delta slope prograded, the active distributary of the Elwha River flow into Lake Mills migrated laterally across the width of the basin, causing the active portion of the delta slope to migrate accordingly (Figure 7). As a result, the two-dimensional progradation of evenly-spaced foreset beds typically depicted in literature actually consists of a series of complexly interfingering lobes (Nemec, 1990b). Observations of the foreset beds preserved in former Lake Mills (particularly in the vicinity of Boulder Creek) show beds that vary significantly both longitudinally and laterally, depending on proximity to tributary inputs, main distributary flow, reservoir morphometry, and water depth (accommodation space). Additionally, evidence of debris flows (Facies G3) and other mass wasting deposits into the reservoir provide triggers for delta slope avalanching not directly tied to flow events (and with the potential for relatively localized influence). Further, observation of the F1 facies discussed above shows that sandy interbeds are thickest and most plentiful with proximity to the delta slope along the main longitudinal axis of the reservoir, suggesting a dependence on the location of active delta distributary.

Erosion and delta progradation associated with two drawdown experiments, as well as non-run of the river operations (for example, in 1956(?); Figure 7) or drought years should be preserved in the reservoir sediments. The progradation of the delta during the 1989 and 1994 drawdown experiments were well documented (Childers et al., 2000; however, no formal stratigraphic descriptions were made at the time, and most strata potentially recording these sequences had been eroded or were thickly covered with coarse-grained sediment by the summer of 2014, when this field work was conducted. However, mouth bars forming the delta top in the 1990 aerial photograph (one year after the 1989 drawdown experiment; Figure 7) stand in contrast to the sharp delta front depicted in the 2009 aerial photograph and our geomorphic mapping (Figure 6A). We hypothesize that this mouth-bar morphology (similar to that observed in former Lake

Aldwell; discussed below) reflects the shallower conditions created by the drawdown delta, resulting in progradation by mouth-bar deposit and the deposition of sand higher in the reservoir body (Wright, 1977).

No evidence of transgressive-regressive sequences was observed in the limited, marginal foreset beds representing the progradation of the main delta that were exposed in 2014 except for secondary deposits resulting from dam removal activities; however, this may be due to the poor preservation of sediments along the main axis of the reservoir. A complete section in Cat Creek, a tributary inflow located near the upstream end of former Lake Mills, shows the interbedding of several well-sorted, sandy gravel deposits between fine-grained prodelta deposits (Figure 9C). Aerial photographs of the reservoir (Figure 7) show that the Cat Creek delta had been filled and stably vegetated since the 1970s but may have been subject to a drawdown event in 1956. Given the location of Cat Creek in the uppermost reservoir, any subsequent low-water periods would most likely have been expressed as erosional gaps in the sediment record.

Additional evidence of low-water periods in former Lake Mills is preserved by the occurrence of several laterally-extensive sandy interbeds within the distal portion of the main lacustrine basin (Figure 15). These interbeds were observed in a cross section with complete exposure to the base of the reservoir sediments but with an upper unconformity. Given the pattern of a single isolated bed, separated by approximately 1 m of fine-grained sedimentation, followed by three closely-spaced beds, it is tempting to assign these interbeds to a >10 year flood which occurred in 1950 (Figure 2), followed by the drawdown experiments of 1989 and 1994 and the >50 year flood of 2007, which are in turn overlain by coarse-grained, dam-removal related deposition. However, the observed bed spacing does not conform with the nearly 50% increase in sedimentation rate from 1927 to 1994 and 1994 to 2010 estimated by Bountry et al. (2011) and offers no evidence of other ~10 year floods documented in the Elwha hydrograph.

Further, evidence from the lacustrine basin in former Lake Aldwell suggests that drawdown deposits associated with dam removal produced thick (>2 m in several instances) accumulations of laminated silt deposits in single events. This suggests that the lowermost interbed could thus be the result of the 1994 drawdown experiment and the upper interbeds evidence of dam removal-related delta progradation. However, in this scenario, both the 1989 drawdown experiment and the 2007 flood are unaccounted for. Given the evidence of drawdown events in both Cat Creek and the lacustrine basin of the reservoir, we include a hypothetical transgressive-regressive sequence in our conceptual model of reservoir sedimentation (Figure 10A) but note that this is an area worthy of additional study in other systems.

2.7.2 Lake Aldwell

In contrast to former Lake Mills, which closely approximates the ideal Gilbert delta in both morphology and facies architecture, the depositional portrait of former Lake Aldwell is significantly more complex (Figure 10B). As the result of a shallower basin, sedimentation processes in former Lake Aldwell tend to be more influenced by bed friction than in former Lake Mills, resulting in a shoal-water, mouth-bar style of delta progradation characterized by active, channelized distributaries depositing large bodies of sand that interfinger to form a delta front (Wright, 1977). Additionally, the interpretation of sediment deposition in former Lake Aldwell is complicated by the influence of two major exogenic processes not observed in former Lake Mills: the 1927 closure of Glines Canyon Dam upstream and catastrophic influx of sediment from non-fluvial sources from a large landslide into the upper reservoir sometime before 1976.

The basin gradient at the head of former Lake Aldwell is significantly lower than in former Lake Mills, which is headed by the steeply-dipping Rica Canyon (gradient ~0.006), creating a comparatively flat, shallow upper reservoir (Figure 5C). At the time of dam removal, the active delta in former Lake Mills was characterized by a broad delta top, apparently prograding by the deposition of middle-ground and lunate mouth bars without distinct foreset (Figure 6B). The active bars were characterized by a gradual transition from sandy gravels in the distributary channel to coarse sands, interbedded with silt and laminated organics that probably represent deposition during the waning limb of high flow events. The mouth bars themselves appear to have been characterized by well-sorted sands distally (Facies S3; similar in nature to the S3 sands in former Lake Mills, but not associated with foreset beds), cut by broad, undulatory channels typically characterized by laterally-accreted coarse organics in a sandy matrix. This style of progradation is commonly associated with shallow water and may be referred to as 'shoal-water' or 'shelf-type' deposits (Westcott and Etheridge, 1990; Nemec, 1995a; Reading and Collinson, 1996); when characterized by lunate bars, it is also indicative of of inertial deposition with "small to moderate bed load" (Wright, 1977; p. 866).

In contrast to former Lake Mills, the "striped mudstone" (F1) facies is almost entirely absent in former Lake Aldwell. This may be a function of both reduced sand supply and lower gradient. Incoming flood waters probably carried both less sediment and encountered little sand available for entrainment and redistribution at the delta mouth due to the upstream capture by Glines Canyon Dam. Thus, plunging summer currents would encounter less sediment available for reworking and transport into the reservoir basin. Additionally, the absence of foreset beds in the former Lake Aldwell delta suggests that gravity-driven transport (whether through continual sediment avalanching, oversteepening, or either of these processes' evolution to a fully turbulent density current) was not a significant process in the transport of sand to the prodelta.

However, this type of delta progradation appears to typify sedimentation in former Lake Aldwell only in its later years. As discussed in Section 3, estimates of sediment storage in former Lake Aldwell were revised from ~2.97 (±1.0) $x10^6 m^3$ (Gilbert and Link, 1995; Bountry et al., 2011) to 4.9 (±1.4) $x10^6 m^3$[1] (Randle et al., 2015). Randle et al. (2015) attributed this revision to "findings from the newly exposed landscape following dam removal that revealed additional reservoir sedimentation [in areas] which were previously mapped as fluvial landforms and predam terraces." These fluvial landforms and predam terraces were identified by Gilbert and Link (1995), who correctly determined that there was no reservoir process-based explanation for sediment in the upper portions of former Lake Aldwell 2.4 and 4.9 m above the maximum operating water surface elevation. Based on this evidence, the juxtaposition of fine-grained sediments (i.e., reservoir sediments) immediately over river cobbles, and the observation of several rooted stumps with their root flares exposed (indicating little sedimentation), Gilbert and Link mapped a large portion of the upper reservoir as representing pre-dam sedimentation processes (Figure 11B). However, the erosion of massive rooted stumps from within this "predam sediment" following dam removal indicated that it was, in fact, the result of deltaic sedimentation (e.g., Figure 11A). As a result, Randle et al. (2015) included these areas in a revised estimate of sedimentation in former Lake Aldwell.

This estimate of Randle et al. (2015) provides probably the most accurate assessment of sediment volume in former Lake Aldwell; however, without considering the processes involved, it suggests an erroneously high rate of sediment transport by the Elwha downstream of Glines Canyon Dam. The total sediment load to former Lake Aldwell prior to the completion of Glines Canyon Dam was estimated between 1.85×10^5 m^3yr^{-1} (Curran et al., 2009; Bountry et al., 2011) and 2.26×10^5 m^3yr^{-1} (Randle et al., 2015). Assuming a conservative trap efficiency of 0.65 for former Lake Aldwell itself, between 1.20×10^6 and 2.05×10^6 m^3 would have been deposited in Lake Aldwell prior to the 1927 closure of Glines Canyon Dam upstream. This volume represents between 34% and 42% of the total sediment volume estimated by Randle et al. (2015), deposited in only the first 14% of the reservoir's lifespan. However, according to aerial photographs (Figure 7; Figure 11C), an area along the western margin of former Lake Aldwell was inundated by a landslide runout sometime between 1956 and 1976 (providing a mechanism for the anomalously high elevations in this region noted by Gilbert and Link, 1995). Depending on the estimated volume of the landslide deposit discussed above, these figures suggest that as much as half the total Elwha-derived sediment load to former Lake Aldwell would have been delivered in the first 14 years of its existence, while the remaining half while the remaining half was deposited over the course of the remaining 84 years.

The dramatic reduction in sediment supply precipitated by the closure of Glines Canyon Dam is clearly evident in the geomorphic evolution of the delta (Figure 7). Where the subaerial delta had prograded ~640 m into the reservoir by 1939, the rate of progradation (with the exception of the post-1956 landslide into the upper delta plain) in subsequent years was minor. Indeed, from 1995 (the year of a detailed sedimentation study of former Lake Aldwell; Gilbert and Link, 1995) to 2010, the delta evolved so little that the USBR, preparing sedimentation estimates for the upcoming removal of Elwha Dam with a 2010 bathymetric survey, determined no substantive change in the delta (Bountry et al., 2011).

A second and more subtle effect of dams on sediment transport in river systems is to alter the grain size distribution of downstream sediment. Dams like Glines Canyon and Elwha, which were constructed without deep outlets, can be assumed to trap 100% of incoming bedload. However, they pass a variable but significant proportion of fine grained sediment carried in suspension. Thus, while the bedload catchment area of former Lake Aldwell was reduced by 78% with the completion of Glines Canyon Dam (Figure 16), the Glines Canyon dam captured only a portion of fine grained sediment from the upper watershed: the entire 14% of sediment ($2.59x10^4$ m^3yr^{-1}) estimated to escape trapping by Glines Canyon Dam would have been in suspension. As a result, the transport of fine grained sediment through the middle Elwha reach would have been disproportionately enriched in fine sediment post-1927.

The sediments of former Lake Aldwell show evidence of this shift in sediment regime. As calculated by Randle et al. (2015), the total sediment load in former Lake Aldwell was composed of 53% fine-grained sediment and 47% coarse-grained sediment, while former Lake Mills was composed of 56% coarse-grained sediment and 43% fine-grained sediment. Gilbert and Link (1995) noted accumulations of fine-grained sediments directly over coarse gravels in channels in the main delta and Indian Creek delta areas during underwater dives in 1994 and 1995; a similar record is preserved in stratigraphic sections of the delta plain. This juxtaposition probably records the abrupt shift in sediment regime resulting from the closure of Glines Canyon Dam. Additionally, the absence of the F1 facies in former Lake Aldwell (which comprises the most prominent prodelta facies in former Lake Mills) probably reflects the lower proportion of available sand vs. silt between the two reservoirs.

Additionally, as discussed above, the delta in former Lake Aldwell was well-developed by 1939 (Figure 7), in keeping with the high incoming sediment load prior to the completion of Glines Canyon Dam. At that time, the subaerial delta appears to have been characterized by a relatively lobate delta margin, which is more typical of Gilbert-style accumulation than shelf-type deltaic deposition, and is similar to former Lake Mills (Figure 6). Further, marginal exposures in the upper portion of former Lake Aldwell show a well-developed tripartite Gilbert sequence, consisting of gravel foreset beds prograding over fine-grained basin deposits and overlain by subhorizontal, coarse-grained topset beds (Figure 14). These foreset beds are lower-gradient than those in former Lake Mills, which probably reflects the lower gradient of the Aldwell basin, but provide evidence of Gilbert-style sedimentation processes early in the reservoir's history.

We interpret the evolution of former Lake Aldwell from Gilbert-style to mouth-bar progradation, accompanied by significant reworking of the delta top (Figure 10B), to reflect both a natural shallowing of the reservoir basin and the 1927 shift in sediment regime. The presence of Gilbert-style foresets and surface morphology show that, despite the relatively shallow nature of the former Lake Aldwell basin, Gilbert-style deposition was active for a period in former Lake Aldwell. With the closure of Glines Canyon Dam, this deltaic deposition was apparently overprinted with the characteristics of a fine-grained, sediment-limited system.

2.8 Summary and Conclusions

The removal of Glines Canyon and Elwha Dams represent, to our knowledge, the first opportunity to examine the composition and architecture of reservoir sediments through direct, spatially comprehensive observation, providing a window into the structure of reservoir sediments, the processes involved, and the evolution of sedimentation styles over the lifetime of a reservoir.

Former Lake Mills probably represents the simplest end member of reservoir sedimentation. Given its relatively simple perimeter, long, narrow morphology, pristine watershed, and operational history as predominantly run-of-the-river, former Lake Mills was similar to a deep-water, glacier-carved lake, making it interpretable in the context of the classic Gilbert delta paradigm. Gilbert-style deltas, as observed in former Lake Mills, are characteristic of abundant coarse-grained deposition into deep, typically fresh-water basins (Nemec, 1990a); as described by the USBR, this paradigm forms the basis for the "typical" reservoir (Strand and Pemberton, 1987).

Given the relative simplicity of this depositional model, the excellent hydrograph record, the historical operation of Glines Canyon Dam for near-constant-head, and the rich stratigraphic dataset described herein, former Lake Mills provides an opportunity to assess our understanding of the dynamics of natural Gilbert-style systems and the basin-wide correlation of facies. The use of marker beds for stratigraphic correlation across systems is common in investigations of marine and lacustrine environments both ancient and modern. For example, with the aid of detailed isotopic dating, Ambers (2001) was able to tie laterally-continuous sediment horizons to individual flood events in the reservoir sediments of Lake Dorena, a flood control reservoir on the Row River in Oregon, providing excellent age control on sediments and the ability to make detailed interpretations of the influence of land use change on the reservoir. However, the lateral and longitudinal variability in the reservoir sediments of former Lake Mills, as well as the stochastic nature of delta slope failure, and variety of endo- and exogenic influences on sediment transport suggests that correlation of individual flow events in systems this dynamic may be more speculative than currently appreciated. While we identified evidence of transgressive/regressive sequences within the sediments of former Lake Mills, we could not conclusively correlate them to either known flood or drawdown events. While this may be a function of the marginal- and bottom-sediment bias of our dataset, as more dams are removed worldwide, additional opportunities for the study of cross-basin correlation will yield a rich field of study.

In contrast to former Lake Mills, the sediments of former Lake Aldwell were characterized by complex facies architecture influenced by the 1) the major reduction in total sediment load following the upstream closure of Glines Canyon Dam, 2) the relative fining of the remaining sediment load due to differences in the rate of bedload vs. suspended load capture by the dam, and 3), the influx of a significant landslide-runout to the upper delta plain. Exposures of Gilbert-style tripartite deltaic assemblages, as well as the evolution of the surface expression of the delta plain, suggest that former Lake Aldwell was characterized by a high-volume, bedload-dominated Gilbert-style delta prior to the upstream closure of Glines Canyon Dam in 1927, after which it was overprinted with the characteristics of a fine-grained, sediment-starved system dominated by mouth-bar, shoal-water style sedimentation. While some of the drivers influencing former Lake Aldwell are inevitably case-specific, the resulting delta represents a system not found in natural systems: that of a steep-profiled but fine-grained system. Existing frameworks developed for lacustrine systems do not describe these systems well, suggesting that robust characterization of reservoir sedimentation in many systems requires the development of new conceptual frameworks.

Additionally, the disparity between sediment volume estimates completed before vs. those completed after dam removal (Gilbert and Link, 1995; Bountry et al., 2011; Randle et al., 2015) illustrate the importance of understanding both endo- and exogenic process dynamics when assessing sedimentation rate and characteristics in depositional systems. Without recognizing the presence of a landslide deposit in the upper delta of former Lake Aldwell, Gilbert and Link (1995) made the obvious conclusion that sediments above the normal reservoir pool elevation could not have been emplaced by reservoir processes and were thus the result of pre-dam fluvial terraces. However, this conclusion then led to the erroneous assumption that abrupt transitions in sedimentation style could only represent the transition from fluvial to reservoir processes rather than an abrupt shift in the sediment regime during the lifespan of the reservoir. Similar to the landslide deposits, without accounting for extremely high sedimentation rates prior to the closure of Glines Canyon Dam, the extensive sedimentation of the upper Aldwell delta prior to 1927 would appear to have no mechanism and also require the alternate explanation of pre-dam deposition.

Again, while the drivers of major changes in sediment regime to former Lake Aldwell are case-specific, given the prevalence of multi-dam systems worldwide (Minear and Kondolf, 2009; Lehner et al., 2011; Foley et al., 2017), a majority of the world's reservoirs can be expected to have been subject to abrupt reductions in sediment regime. Conversely, logging, watershed development, mining activities, or naturally-caused landslides upstream have all been cited as drivers of increased sedimentation in reservoirs and natural lakes (Ambers, 2001; Snyder et al. 2004, 2006; Thothong et al., 2011; Bountry et al., 2011). Our analysis of the sediments in former Lakes Aldwell and Mills suggests that these changes are recorded by both the geomorphic expression of delta progradation and the facies architecture of the systems; however, the nature of this evolution is complex and interpretation of event horizons may be hindered by the heterogeneous nature of sedimentation. The increasing number of dam removals underway worldwide (Foley et al., 2017) offers the opportunity to develop robust conceptual models of sedimentation across a variety of reservoir systems, providing better tools for the prediction of reservoir sedimentation and offering insight into interpretation of lake sediments both modern and ancient.

2.9 Acknowledgements

We wish to thank Andrew Ritchie, Tim Randle, Jennifer Bountry, and Seth Wing for field assistance and access to unpublished data. We also thank Roy Haggerty and Sarah Lewis for valuable discussion and Caroline Nash for the title inspiration.

2.10 References Cited

Acker, S.A., Beechie, T.J., and Shafroth, P.B., 2008, Effects of a Natural Dam-Break Flood on Geomorphology and Vegetation on the Elwha River, Washington, U.S.A: Northwest Science, v. 82, p. 210–223, doi: 10.3955/0029-344X-82.S.I.210.

Ambers, R.K., 2001, Using the sediment record in a western Oregon flood-control reservoir to assess the influence of storm history and logging on sediment yield: Journal of Hydrology, v. 244, p. 181–200.

Batt, G.E., Brandon, M.T., Farley, K.A., and Roden-Tice, M., 2001, Tectonic synthesis of the Olympic Mountains segment of the Cascadia wedge, using two-dimensional thermal and kinematic modeling of thermochronological ages: Journal of Geophysical Research, v. 106, B11, p. 26,731-26, and 746.

Bountry, J., Ferrari, R., Wille, K., and Randle, T.J., 2011, 2010 Survey Report for Lake Mills and Lake Aldwell on the Elwha River, Washington: United States Department of the Interior Bureau of Reclamation Technical Report SRH-2010-23, 66 p.

Brandon, M.T., Roden-Tice, M.K., and Garver, J.I., 1998, Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, northwest Washington State: GSA Bulletin, v. 110, p. 985–1009.

Bromley, C., 2008, The morphodynamics of sediment movement through a reservoir during dam removal: University of Nottingham, http://etheses.nottingham.ac.uk/1244/ (accessed December 2014).

Bunn, S.E., and Arthington, A.H., 2002, Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity: Environmental Management, v. 30, p. 492–507.

Childers, D., Kresch, D.L., Gustafson, S.A., Randle, T.J., Melena, J.T., and Cluer, B., 2000, Hydrologic data collected during the 1994 Lake Mills drawdown experiment, Elwha River, Washington: United States Geological Survey Report 99–4215, 115 p.

Colella, A. and Prior, D.B. (eds.), 1990, Coarse-grained deltas. Special Publication Number 10 of the International Association of Sedimentologists, Blackwell Scientific Publications, Boston, 357 pp.

Curran, C.A., Konrad, C.P., Higgins, J.L., and Bryant, M.K., 2009, Estimates of sediment load prior to dam removal in the Elwha River, Clallam County, Washington: http://pubs.usgs.gov/sir/2009/5221/ (accessed March 2015).

Downing, J.A., Prairie, Y.T., Cole, J.J., Duarte, C.M., Tranvik., L.J., Striegl, R.G., McDowell, W.H., Kortelainen, P., Caraco, N.F., Melack, J.M, Middelburg, J.J. (2006). The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography,* 51(5), 2388-2397. https://doi.org/10.4319/lo.2006.51.5.2388

Draut, A.E., Logan, J.B., and Mastin, M.C., 2011, Channel evolution on the dammed Elwha River, Washington, USA: Geomorphology, v. 127, p. 71–87, doi: 10.1016/j.geomorph.2010.12.008.

Duda, J.J., Freilich, J.E., and Schreiner, E.G., 2008, Baseline Studies in the Elwha River Ecosystem Prior to Dam Removal: Introduction to the Special Issue: Northwest Science, v. 82, p. 1–12, doi: 10.3955/0029-344X-82.S.I.1.

Duda, J.J., Warrick, J.A., and Magirl, C.S., 2011, Coastal habitats of the Elwha River, Washington- Biological and physical patterns and processes prior to dam removal: U.S. Geological Survey Scientific Investigations Report 2011–50120, 265 p.

Foley, M.M., Magilligan, F.J., Torgersen, C.E., Major, J.J., Anderson, C.W., Connolly, P.J., Wieferich, D., Shafroth, P.B., Evans, J.E., Infante, D. and Craig, L.S., 2017. Landscape context and the biophysical response of rivers to dam removal in the United States. PLOS One 12(7), E0180107.

Forel, F.A., 1892, Le Léman - Monographie Limnologique. E. Rouge,Lausanne, Volume 1, 543p.

Gilbert, G.K. (1885). The topographic features of lake shores, in Fifth Annual report of the United States Geological Survey 1883-84,. 69-123.

Gilbert, J., and Link, R.A., 1995, Alluvium distribution in Lake Mills, Glines Canyon Project and Lake Aldwell, Elwha Project, Washington: U.S. Department of the Interior, Elwha Technical Series PN-95-4, 60 p.

Giovanoli, F., 1990, Horizontal transport and sedimentation by interflows and turbidity currents in Lake Geneva, in: Tilzer MM and Serruya C (eds), Large lakes: ecological structure and function. Springer-Verlag, New York, p 175–195.

Graf, W.L., 2005, Geomorphology and American dams: The scientific, social, and economic context: Geomorphology, v. 71, p. 3–26, doi: 10.1016/j.geomorph.2004.05.005.

Grant, G.E., 2012, The Geomorphic Response of Gravel-Bed Rivers to Dams: Perspectives and Prospects, in: Church, M., Biron, P. M., and Roy, A. G., Gravel Bed Rivers: Processes, Tools, Environments (first edition), New York, John Wiley and Sons, p. 165-181.

Grant, G.E., O'Connor, J., and Safran, E., 2017, Excursions in fluvial (dis)continuity: Geomorphology, v. 277, p. 145–153, doi: 10.1016/j.geomorph.2016.08.033.

Hosey, 1990a, Lake Aldwell Bathymetric Map, Engineering Hydraulics, Inc. (for James River II, Inc.), Glines Canyon Project (FERC No. 2683), Job No. 3535-003, dated February 7, 1990, scale 1" = 400', Figure 3.1.

Hosey, 1990b, Lake Mills Bathymetric Map, Engineering Hydraulics, Inc. (for James River II, Inc.), Glines Canyon Project (FERC No. 588), Job NO. 3535-003, dated February 7, 1990, scale 1" = 400', Figure 3.1.

International Commission on Dams (2018). World register of dams: general synthesis. http://www.icold-cigb.net/GB/world_register/general_synthesis.asp, accessed May 28, 2018.

Keith, M.K., Wallick, J.R., Taylor, G., Mangano, J., White, J. and Schenk, L., 2016, Geomorphic responses of gravel bed rivers to fine sediment releases during annual reservoir drawdowns: Spatial patterns and magnitude of aggradation along Fall Creek and Middle Fork Willamette River, Oregon. Abstract EP53C-0984 presented at 2016 Fall Meeting, AGU, San Francisco, California, 12-16 December.

Kloehn, K. K., Beechie, T. J., Morley, S. A., Coe, H. J., and Duda, J.J., 2008, Influence of Dams on River-Floodplain Dynamics in the Elwha River, Washington: Northwest Science, v. 82 (Special Issue), p. 224-235.

Kondolf, G. M., Rubin, Z.K., and Minear, J.T., 2014, Dams on the Mekong: cumulative sediment starvation: Water Resources Research, v. 50, p. 5158-5169, doi: 10.1002/2013WR014651.

Kostic, S., Parker, G., and Marr, J.G., 2002, Role of turbidity currents in setting the foreset slope of clinoforms prograding into standing fresh water: Journal of Sedimentary Research, v. 72, p. 353–362.

Kummu, M., Lu, X.X., Wang, J.J., and Varis, O., 2010, Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong: Geomorphology, v. 119, p. 181–197, doi: 10.1016/j.geomorph.2010.03.018.

Lehner, B., Liermann, C.R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J.C., Rödel, R., Sindorf, N., et al., 2011, High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management: Frontiers in Ecology and the Environment, v. 9, p. 494–502, doi: 10.1890/100125.

Long, W. A. 1975, Salmon Springs and Vashon continental ice in the Olympic Mountains and relation of Vashon continental to Fraser Olympic ice, Olympia: U.S. Forest Service, 123 pp.

Major, J.L., East, A.E., O'Connor, J.E., Grant, G.E., Wilcox, A.C., Magirl, C.S., Collins, M.J., and Tullos., D.D., , 2017, Geomorphic Responses to Dam Removal in the United States – a Two-Decade Perspective, in Tsutsumi, D. and Laronne, eds., Gravel-Bed Rivers: Processes and Disasters: John Wiley & Sons Ltd., p. 355-383.

McNulty, T., 2009. Olympic National Park: A natural istory (second edition), Seattle: University of Washington Press, 384 pp.

Minear, J.T., and Kondolf, G.M., 2009, Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California: TECHNICAL NOTE: Water Resources Research, v. 45, p. n/a-n/a, doi: 10.1029/2007WR006703.

Morris, G.L. and Fan, J., 1997, Reservoir sedimentation handbook, San Francisco: McGraw-Hill.

Mosher, D.C., and Hewitt, A.C., 2004, Late Quaternary deglaciation and sea-level history of eastern Juan de Fuca Strait, Cascadia, Quaternary International, v. 121, p. 23-39.

Munn, M.D., Black, R.W., Haggland, M.A., and Huffman, R.L., 1999, An assessment of stream habitat and nutrients in the Elwha River basin: implications for restoration: United States Geological Survey Water Resources Investigations 98–4223, 38 p.

Nemec, W., 1990a, Deltas – remarks on terminology and classification, in: Collela, A. and Prior, D.B. (eds), Coarse-grained deltas. Special Publication Number 10 of the International Association of Sedimentologists, Blackwell Scientific Publications, Boston, p. 3 – 12.

Nemec, W., 1990b, Aspects of sediment movement on steep delta slopes, in: Collela, A. and Prior, D.B. (eds), Coarse-grained deltas. Special Publication Number 10 of the International Association of Sedimentologists, Blackwell Scientific Publications, Boston, p. 29 – 74.

Nilsson, C., 2005, Fragmentation and Flow Regulation of the World's Large River Systems: Science, v. 308, p. 405–408, doi: 10.1126/science.1107887.

Nilsson, C., and Berggren, K., 2000, Alterations of Riparian Ecosystems Caused by River Regulation: Dam operations have caused global-scale ecological changes in riparian ecosystems. How to protect river environments and human needs of rivers remains one of the most important questions of our time: BioScience, v. 50, p. 783–792.

O'Connor, J.E., Duda, J.J., and Grant, G.E., 2015, One Thousand Dams Down and Counting – a Forty-Year Perspective: Science, v. 348, p. 496 – 497.

Pess, G.R., McHenry, M.L., Beechie, T.J., and Davies, J., 2008, Biological Impacts of the Elwha River Dams and Potential Salmonid Responses to Dam Removal: Northwest Science, v. 82, p. 72–90, doi: 10.3955/0029-344X-82.S.I.72.

Polenz,M., Wegmann, K.W., and Schasse, H.W., 2004, Geologic map of the Elwha and Angeles Point 7.5-minute quadrangles, Clallam County,Washington. Open-File Report 2004-14, scale 1:24,000, Washington Division of Geology and Earth Resources, Olympia, WA.

Pondell, C.R. and Canuel, E.A., 2017, The Role of Hydrodynamic Sorting on the Accumulation and Distribution of Organic Carbon in an Impoundment: Englebright Lake, California, USA: Biogeochemistry, v. 133, p. 129-145.

Randle, T.J., Bountry, J.A., Ritchie, A., and Wille, K., 2015, Large-scale dam removal on the Elwha River, Washington, USA: Erosion of reservoir sediment: Geomorphology, v. 246, p. 709–728, doi: 10.1016/j.geomorph.2014.12.045.

Reading, H.G. and Collinson, J.D., 1996, Clastic Coasts, in: Sedimentary Environments: Processes, Facies and Stratigraphy. Reading, H.G. (ed.), Sedimentary Environments: Processes, Facies and Stratigraphy (third edition), Oxford : Blackwell Science, p. 154-231.

Romans, B.W., Castelltort, S., Covault, JA, Fildani, A, and Walsh, JP, 2016. Environmental signal propagation in sedimentary systems across timescales. Earth-Science Reviews 153: 7-29.

Schmidt, J.C. and Wilcock, P.R., 2008. Metrics for assessing the downstream effects of dams. Water Resources Research 44(4), W04404.

Schuster, J. E., 2005, Geologic map of Washington State, Washington Division of Geology and Earth Resources Geologic Map GM-53. Scale 1:500,000, 1 sheet.

Snyder, N.P., Rubin, D.M., Alpers, C.N., Childs, J.R., Curtis, J.A., Flint, L.E., and Wright, S.A., 2004, Estimating accumulation rates and physical properties of sediment behind a dam: Englebright Lake, Yuba River, northern California: Water Resources Research, v. 40, p. n/a-n/a, doi: 10.1029/2004WR003279.

Snyder, N.P., Wright, S.A., Alpers, C.N., Flint, L.E., Holmes, C.W., and Rubin, D.M., 2006, Reconstructing depositional processes and history from reservoir stratigraphy: Englebright Lake, Yuba River, northern California: Journal of Geophysical Research, v. 111, doi: 10.1029/2005JF000451.

Spicer, R.A., and Wolfe, J.A., 1987, Plant taphonomy of late Holocene deposits in Trinity (Clair Engle) Lake, northern California: Paleobiology, v. 13, p. 227–245.

Strand, R.I. and Pemberton, E.I. (1987). Reservoir sedimentation. In: Design of small dams. United States Bureau of Reclamation Technical Services and Engineering Center, Denver, Colorado, pp. 529-564.

Sturm, M., and Matter, A., 1978, Turbidites and varves in Lake Brienz (Switzerland): deposition of clastic detritus by density currents: Special Publications of the International Association of Sedimentologists, v. 2, p. 147–168.

Syvitski, J.P., Vörösmarty, C.J., Kettner, A.J., and Green, P., 2005, Impact of humans on the flux of terrestrial sediment to the global coastal ocean: Science, v. 308, p. 376–380.

Tabor, R.W., and Cady, W.M., 1978, Geologic map of the Olympic Peninsula, Washington. U.S. Geological Survey Miscellaneous Investigations Series Map I-944, 2 sheets, scale 1: 125,000, Reston, VA.

Tabor, R.W.,1982, Guide to the geology of Olympic National Park (second printing), Seattle: University of Washington Press, 144 p.

Talbot M.R. and Allen, P.A. 1996. Lakes, in: Reading H.G. (ed.), Sedimentary Environments: Processes, Facies and Stratigraphy (third edition): Oxford, Blackwell Science, p. 83–124.

Thonton, K.W., Kimmel, B.L., and Payne, F.E. , eds. (1990). *Reservoir Limnology: ecological* perspectives. Somerset, New Jersey: John Wiley & Sons, Inc.

Thothong, W., Huon, S., Janeau, J., Boonsaner, A., de Rouw, A., Planchon, O., Bardoux, G., and Parkpian, P., 2011. Impact of land use change and rainfall on sediment and carbon accumulation in a water reservoir of North Thailand. Agriculture, Ecosystems and Environment, 140, 521-533. https://doi.org/10.1016/j.agee.2011.02.006

Twichell, D.C., Cross, V.A., Hanson, A.D., Buck, B.J., Zybala, J.G., and Rudin, M.J., 2005, Seismic Architecture and Lithofacies of Turbidites in Lake Mead (Arizona and Nevada, U.S.A.), an Analogue for Topographically Complex Basins: Journal of Sedimentary Research, v. 75, p. 134–148, doi: 10.2110/jsr.2005.011.

U.S. Department of the Interior, Bureau of Reclamation, 1996a, Removal of Elwha and Glines Canyon Dams." U.S. Bureau of Reclamation, Pacific Northwest Region Elwha Technical Series PN-95-7, 90 p.

U.S. Department of the Interior, National Park Service, 1996b, Final Elwha River Ecosystem Restoration Implementation Environmental Impact Statement, Olympic National Park, Port Angeles, Washington.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P., and Syvitski, J.P.., 2003, Anthropogenic sediment retention: major global impact from registered river impoundments: Global and Planetary Change, v. 39, p. 169–190, doi: 10.1016/S0921-8181(03)00023-7.

Walling, D.E., and Fang, D., 2003, Recent trends in the suspended sediment loads of the world's rivers: Global and Planetary Change, v. 39, p. 111–126, doi: 10.1016/S0921-8181(03)00020-1.

Warrick, J.A., Bountry, J.A., East, A.E., Magirl, C.S., Randle, T.J., Gelfenbaum, G., Ritchie, A.C., Pess, G.R., Leung, V., and Duda, J.J., 2015, Large-scale dam removal on the Elwha River, Washington, USA: Source-to-sink sediment budget and synthesis: Geomorphology, v. 246, p. 729–750, doi: 10.1016/j.geomorph.2015.01.010.

Wescott, W.A., Etheridge, F.G. (1990). Fan deltas – alluvial fans in coastal settings. In: Rachocki, A., Church, M.A. (Eds.), Alluvial Fans: A Field Approach. John Wiley Sons, Chichester, pp. 195–212.

Wetzel, R.G., 2001, Limnology (third edition), San Diego: Elsevier, 1006 pp.

Wildman, R.A., Pratson, L.F., DeLeon, M., and Hering, J.G., 2011, Physical, Chemical, and Mineralogical Characteristics of a Reservoir Sediment Delta (Lake Powell, USA) and Implications for Water Quality during Low Water Level: Journal of Environment Quality, v. 40, p. 575, doi: 10.2134/jeq2010.0323.

Wing, S., 2014, Reservoir sediment carbon along the Elwha River after dam removal: University of Washington, https://dlib.lib.washington.edu/researchworks/handle/1773/26432 (accessed August 2016).

Wright, L.D., 1977, Sediment transport and deposition at river mouths: a synthesis: Geological Society of America Bulletin, v. 88, p. 857–868.

Yang, X., and Lu, X.X., 2014, Estimate of cumulative sediment trapping by multiple reservoirs in large river basins: An example of the Yangtze River basin: Geomorphology, v. 227, p. 49–59, doi: 10.1016/j.geomorph.2014.01.014.

2.11 Figures

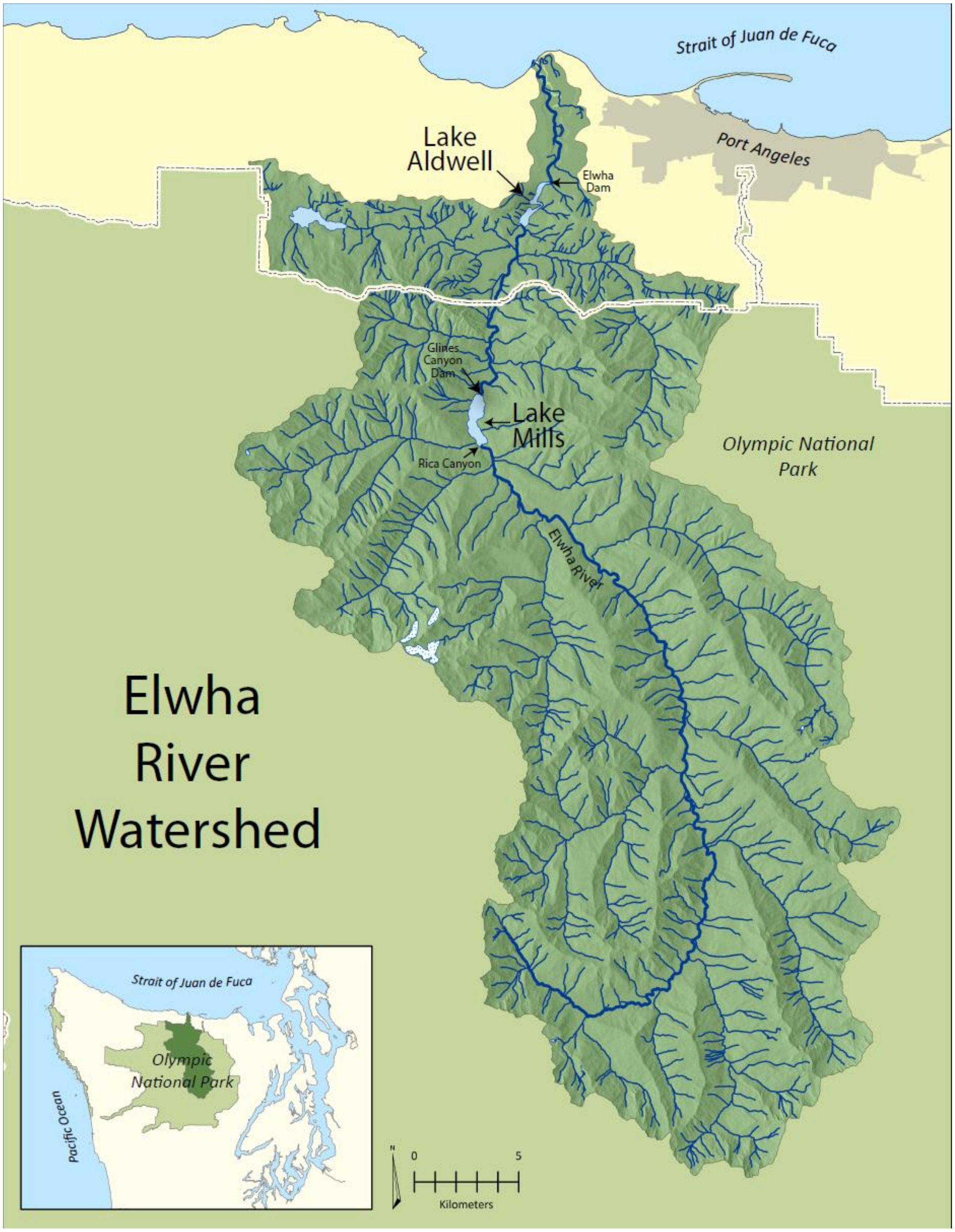


Figure 2-1. Map showing location of Elwha watershed on the Olympic Peninsula of western Washington State. Mainstem Elwha River with tributaries, former Lakes Mills and Aldwell indicated in blue. Eighty-three percent of the watershed is within Olympic National Park.

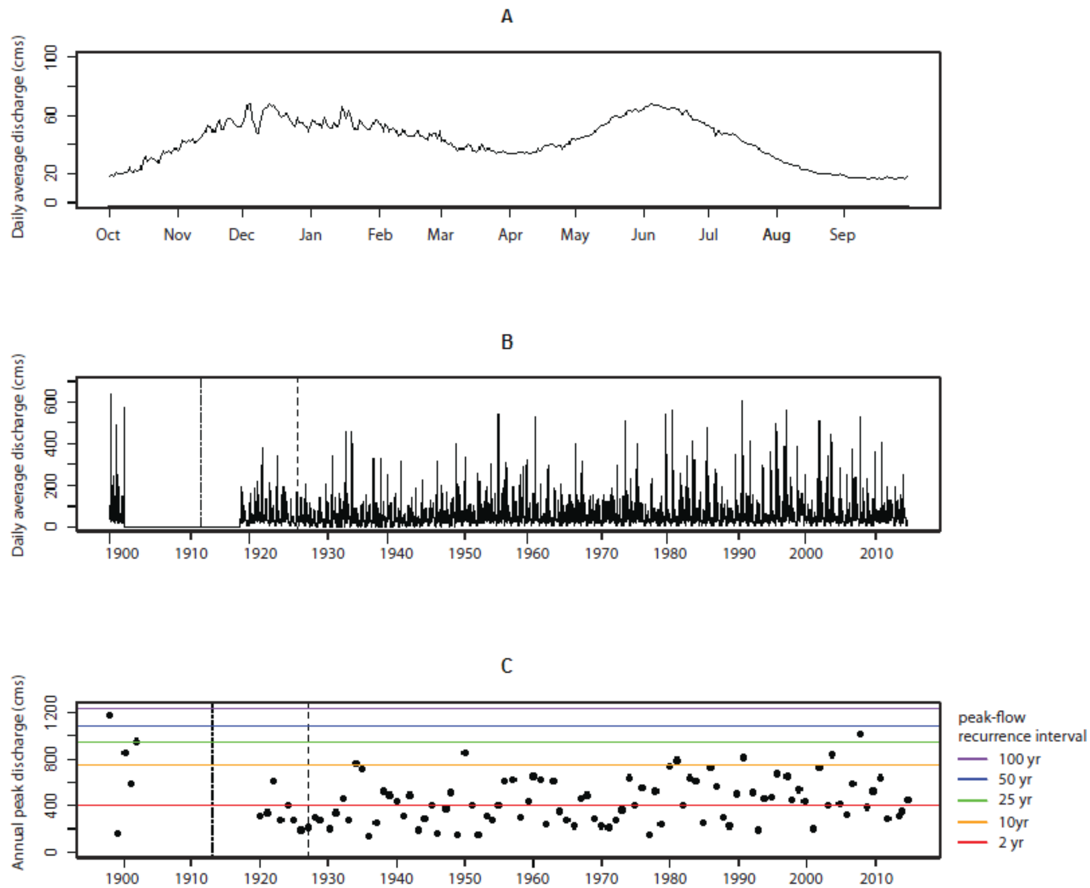


Figure 2-2. Hydrographs of the Elwha River at McDonald Bridge (USGS gaging station 12045500). A) Daily discharge, averaged over length of record, B) Complete record, 1897-1901, 1918- 2014. Dashed lines indicate closure of Elwha Dam (1913) and Glines Canyon Dam (1927). C) Annual peak discharge with estimated peak-flow recurrence interval (Duda et al. 2011). Flood of record 1180 cms, recorded November 18, 1897. Largest flood during the reservoir era (second largest ever measured) recorded December 3, 2007 at 1020 cms.

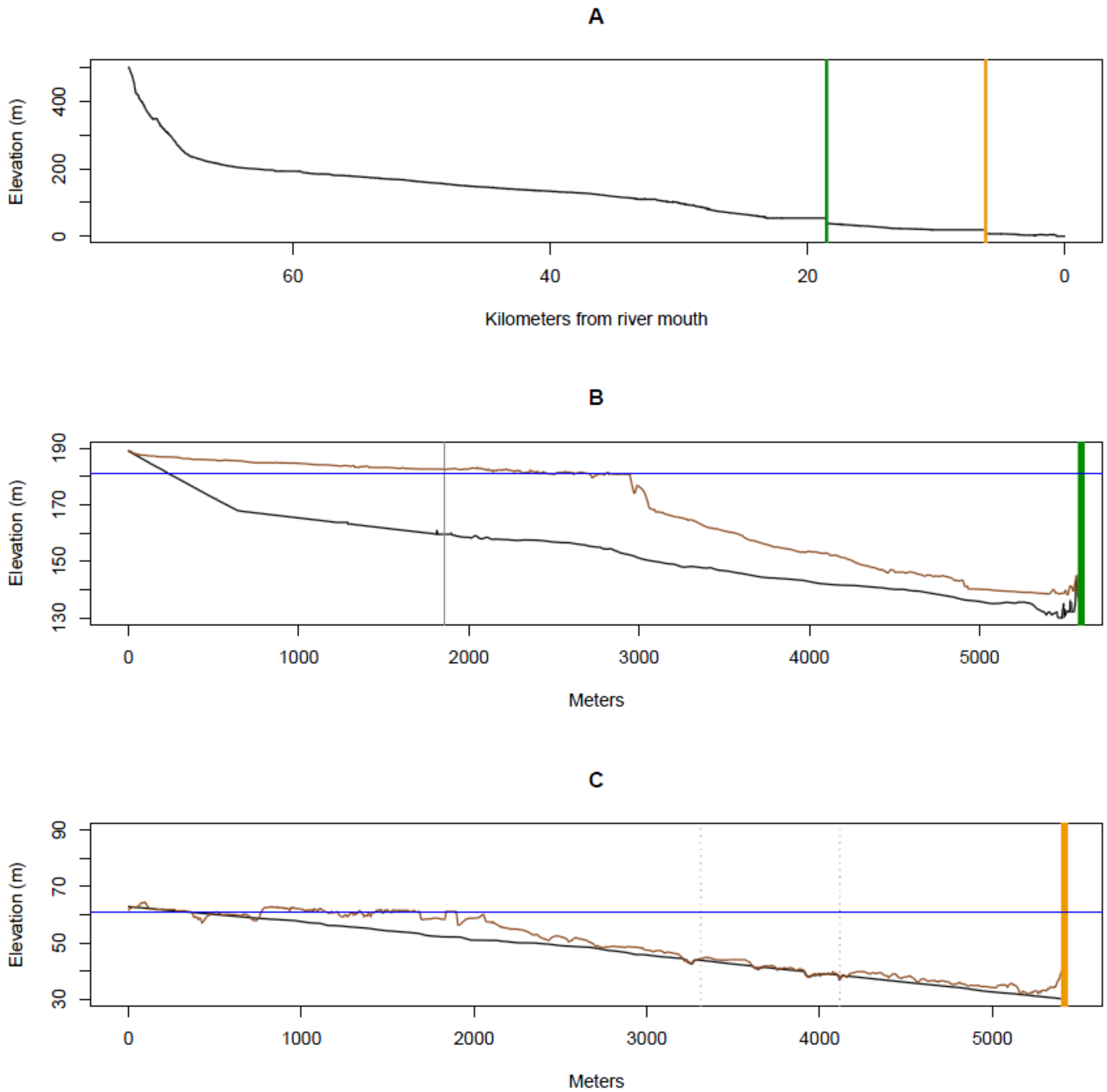


Figure 2-3. Delta morphology, 2009 (A), sediment accumulation, dam closure to 2010 (B), and stratigraphic section location (black crosses), 2014 (C). Sediment accumulation data adapted from Bountry et al. (2011). Orthophoto derived from 2014 Structure from Motion analysis; unpublished data, National Park Service.

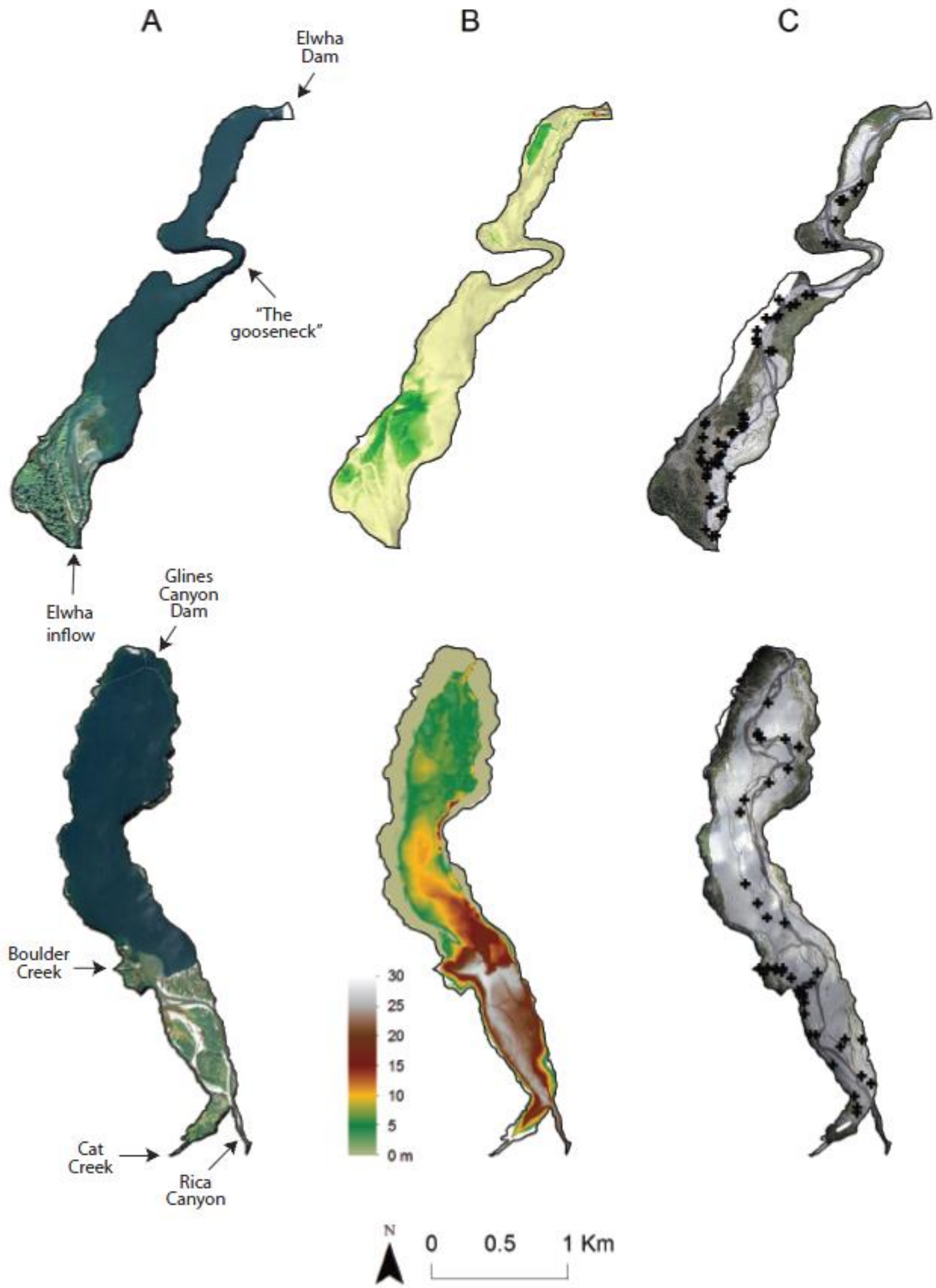


Figure 2-4. Dam crest and water surface elevations during stepped removal of Glines Canyon (A) and Elwha (B). Loss of Lake Aldwell (i.e., dam control of water surface elevation) occurred March 9, 2012. Loss of Lake Mills occurred October 12, 2013. Adapted from Randle et al., 2015.

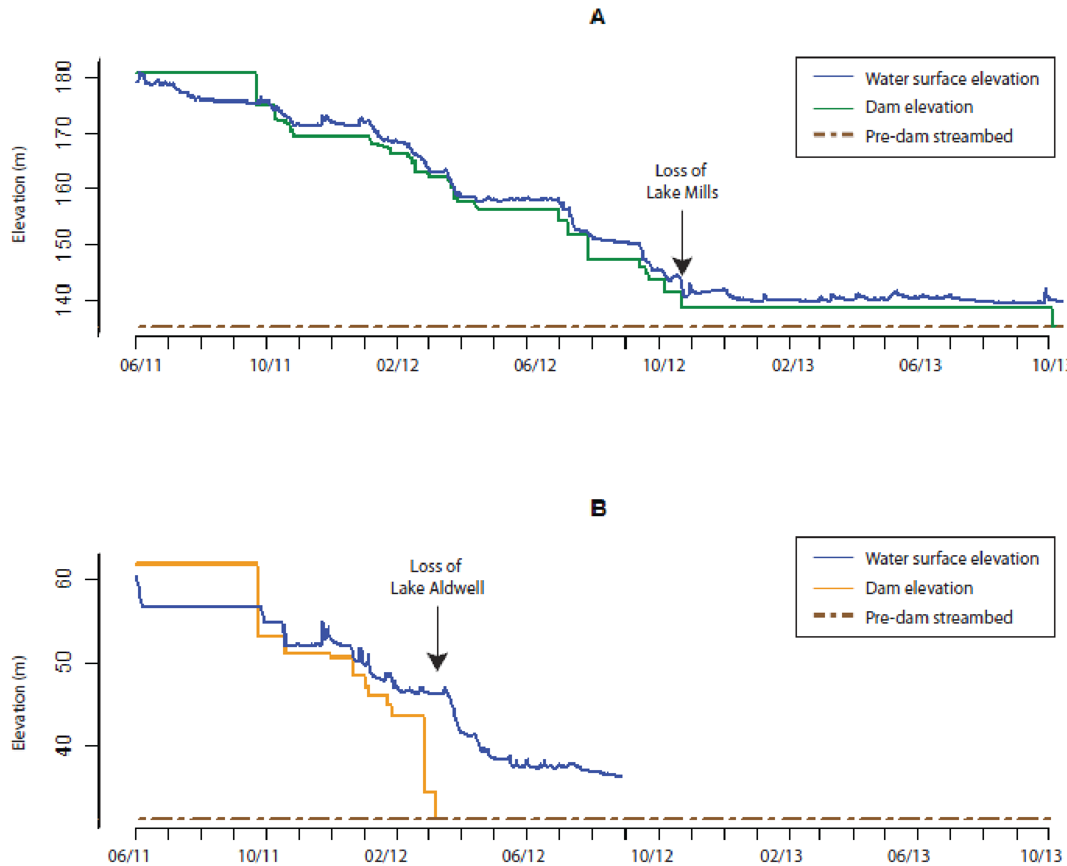


Figure 2-5. Thalweg profiles showing: A) Elwha River gradient, Mount Olympus to river mouth at Strait of Juan de Fuca. Dams indicated in green (Glines Canyon) and yellow (Elwha); shaded area indicates length of reservoir B) Profile of Lake Mills and C) Profile of Lake Aldwell. Pre-dam elevations indicated in blackPre-removal, 2010 surveyed elevations indicated in brown. Typical water surface elevation indicated in blue. Glines Canyon (green) and Elwha (brown) dams indicated with vertical lines. Solid vertical line (B) indicates lowermost extent of Rica Canyon, where Lake Mills basin opens. Dashed vertical lines (C) indicate “gooseneck” constricted region of Lake Aldwell. Thalweg profiles were computed along the estimated pre-dam thalweg using the pre-dam DEMs created by Bountry et al. (2011) and orthophotos from the National Park Service.

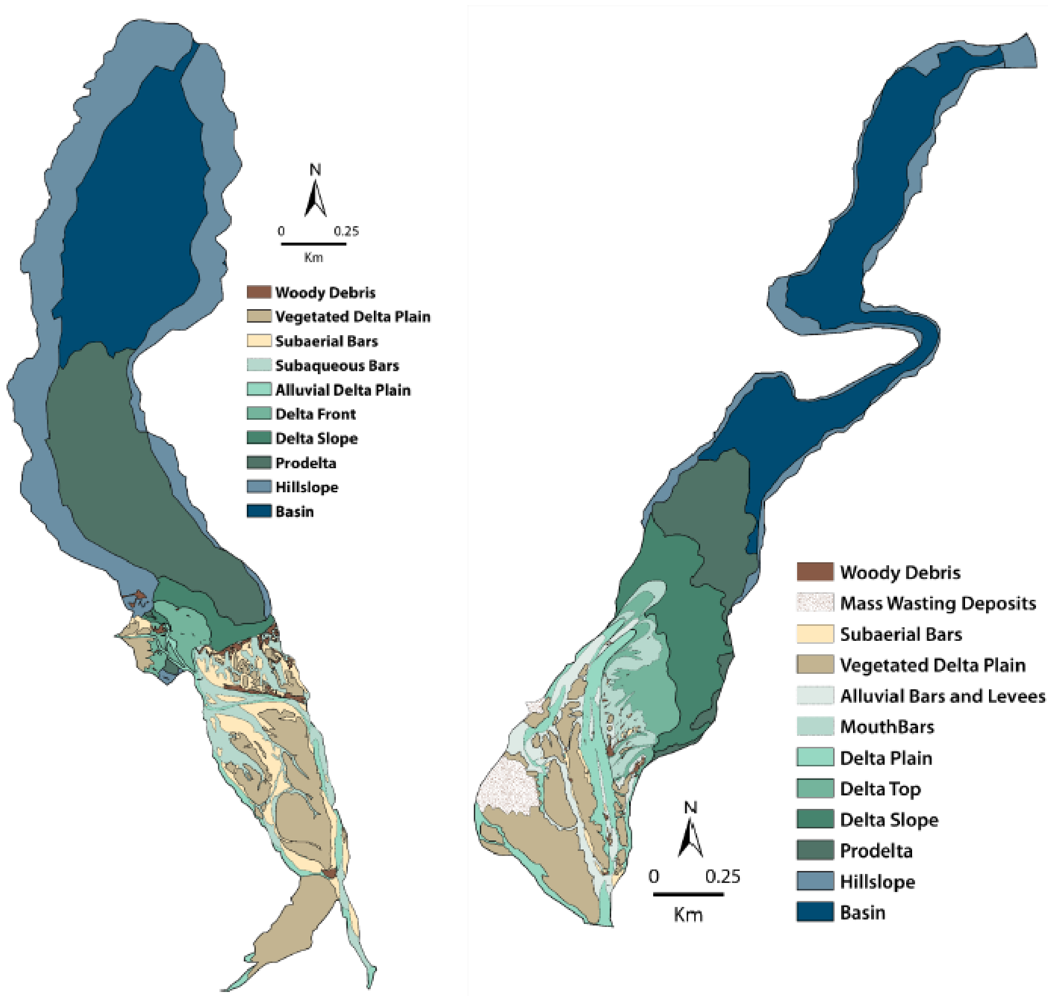


Figure 2-6. Geomorphic map of Lake Mills (A) and Lake Aldwell (B) based on 2006 and 2009 aerial photographs. Heavy outline indicates depositional area (basin, hillslope, prodelta, etc.). Light outline indicates geomorphic feature within depositional area. Warm colors are subaerial; cool colors are subaqueous.

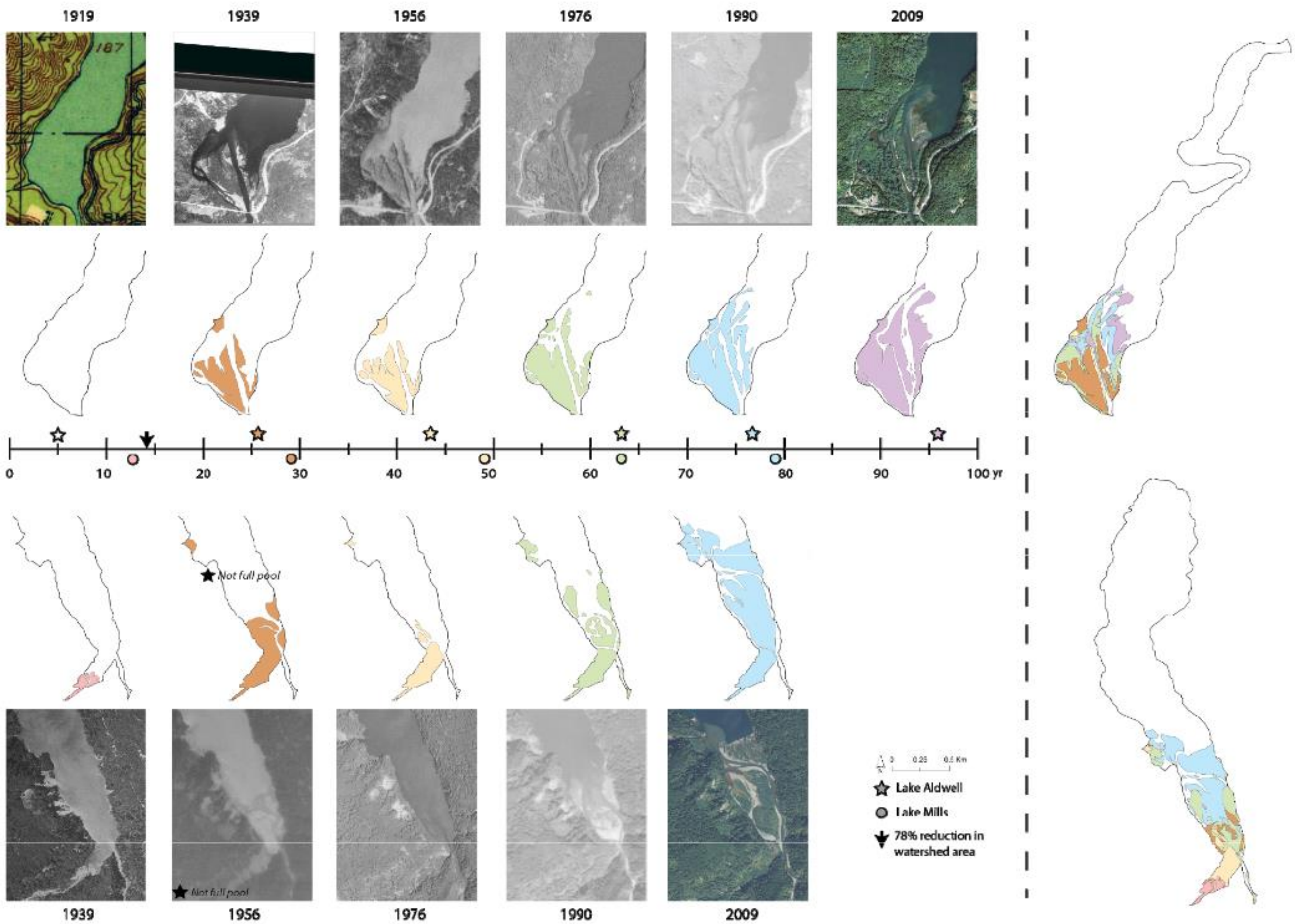


Figure 2-7. Relative subaerial delta progradation rate and morphology, Lake Aldwell (above) and Lake Mills (below). Colors indicate reservoir age (years since dam closure); absolute date given adjacent to aerial photograph.

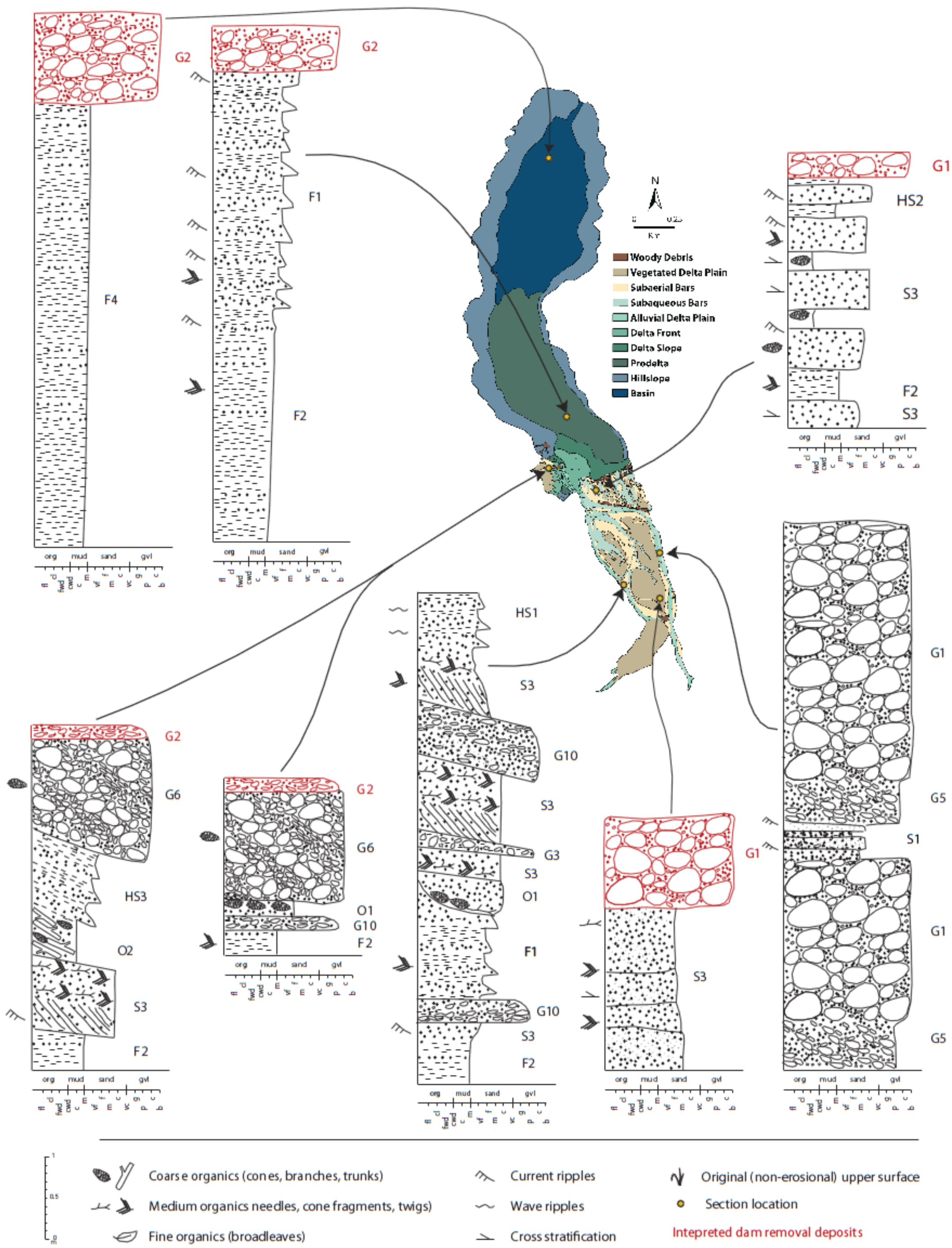


Figure 2-8. Representative stratigraphic sections within geomorphic depositional zones, former Lake Mills. Explanation of facies terminology is given in Table 2. Detailed view of geomorphic map given in Figure 6.

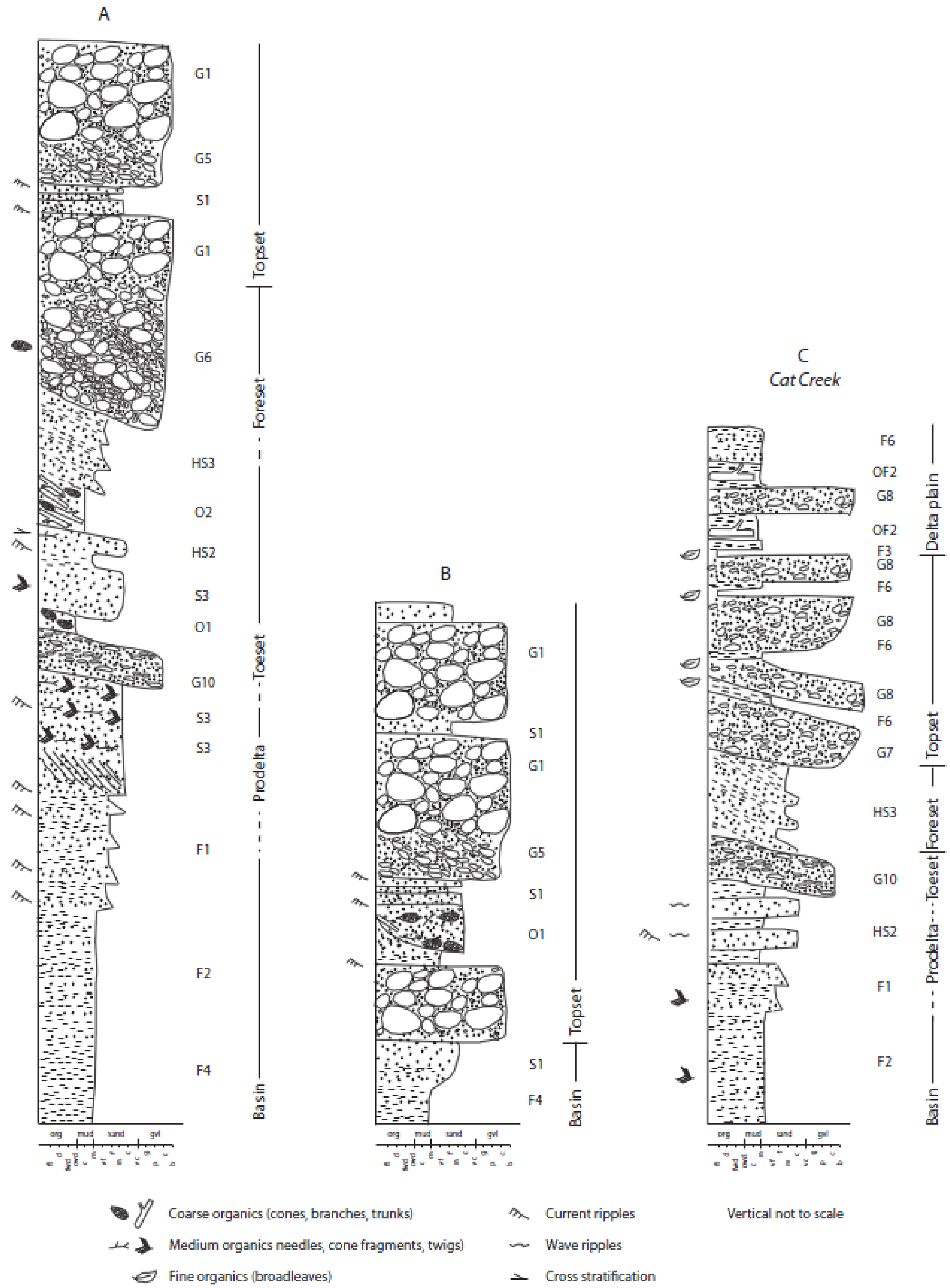


Figure 2-9. Idealized stratigraphic columns, former Lake Mills. A) represents a composite stratigraphic column occurring in the main body of the basin, while B) represents a composite column that would occur closer to the head of the reservoir (near Rica Canyon). C) is a composite column from the Cat Creek tributary, the only complete, exposed section preserved in reservoir sediments as of 2014

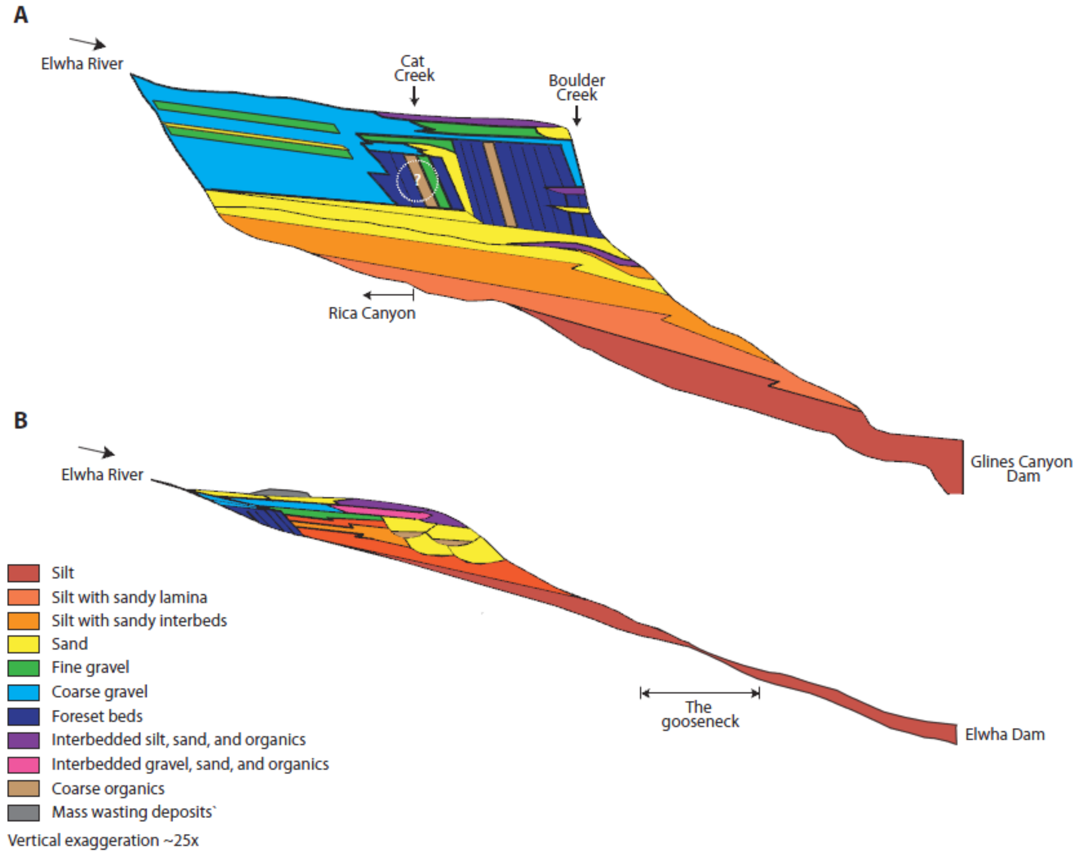


Figure 2-10. Conceptual, cartoon model of cross-sectional sedimentation patterns in former Lakes Mills (A) and Aldwell (B). Total sediment accumulation profiles are approximately representative of actual conditions in 2010 but all stratigraphy is interpretive.

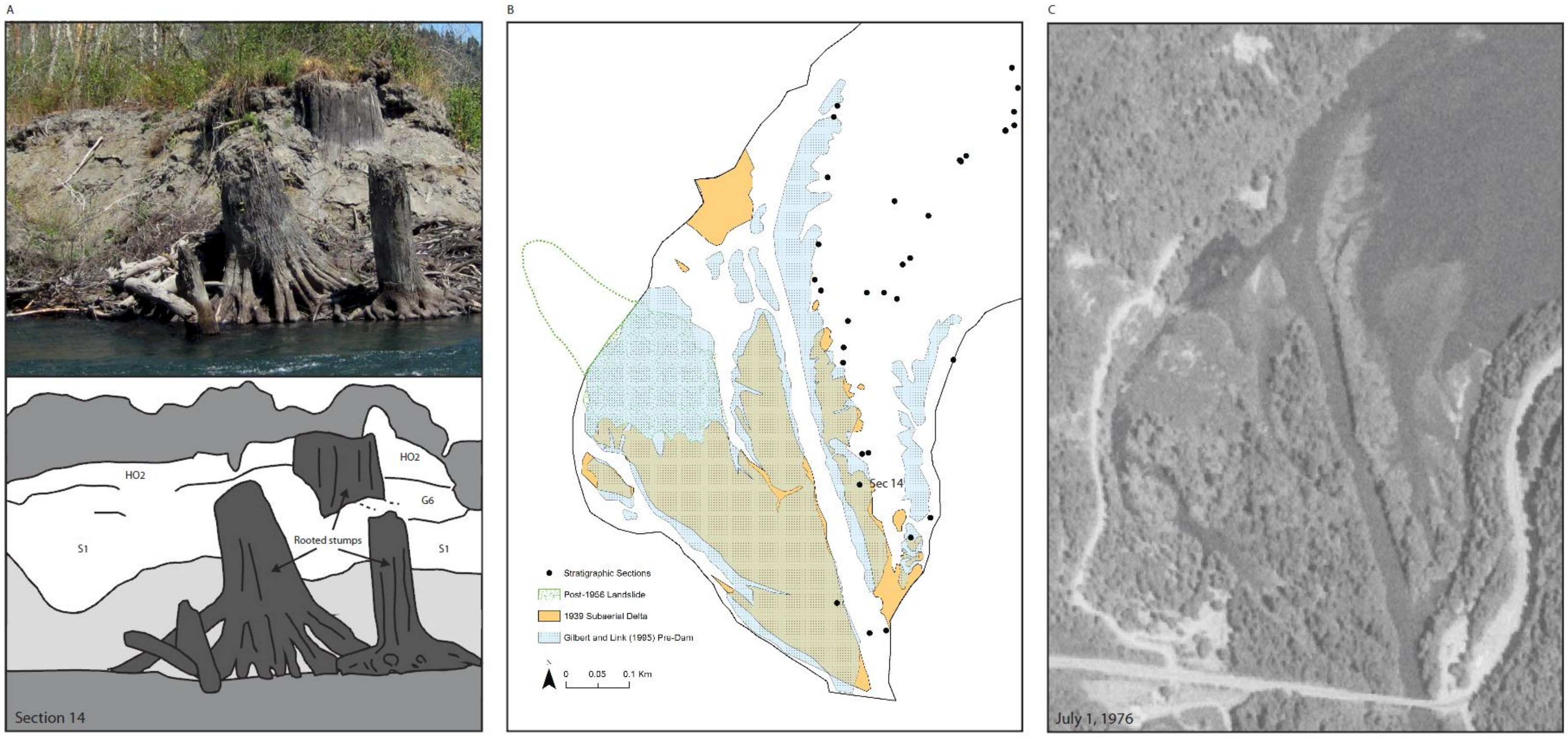


Figure 2-11. Evidence of extensive upper delta plain development in former Lake Aldwell early in the reservoir history. A) rooted, logged stumps eroding from delta plain sediments (location in 11B), B) landslide deposits, delta extent as of 1939, and “pre-dam” extent as mapped by Gilbert and Link (1995), C) July, 1976 aerial photograph showing clear outline of slope failure and runout zone.

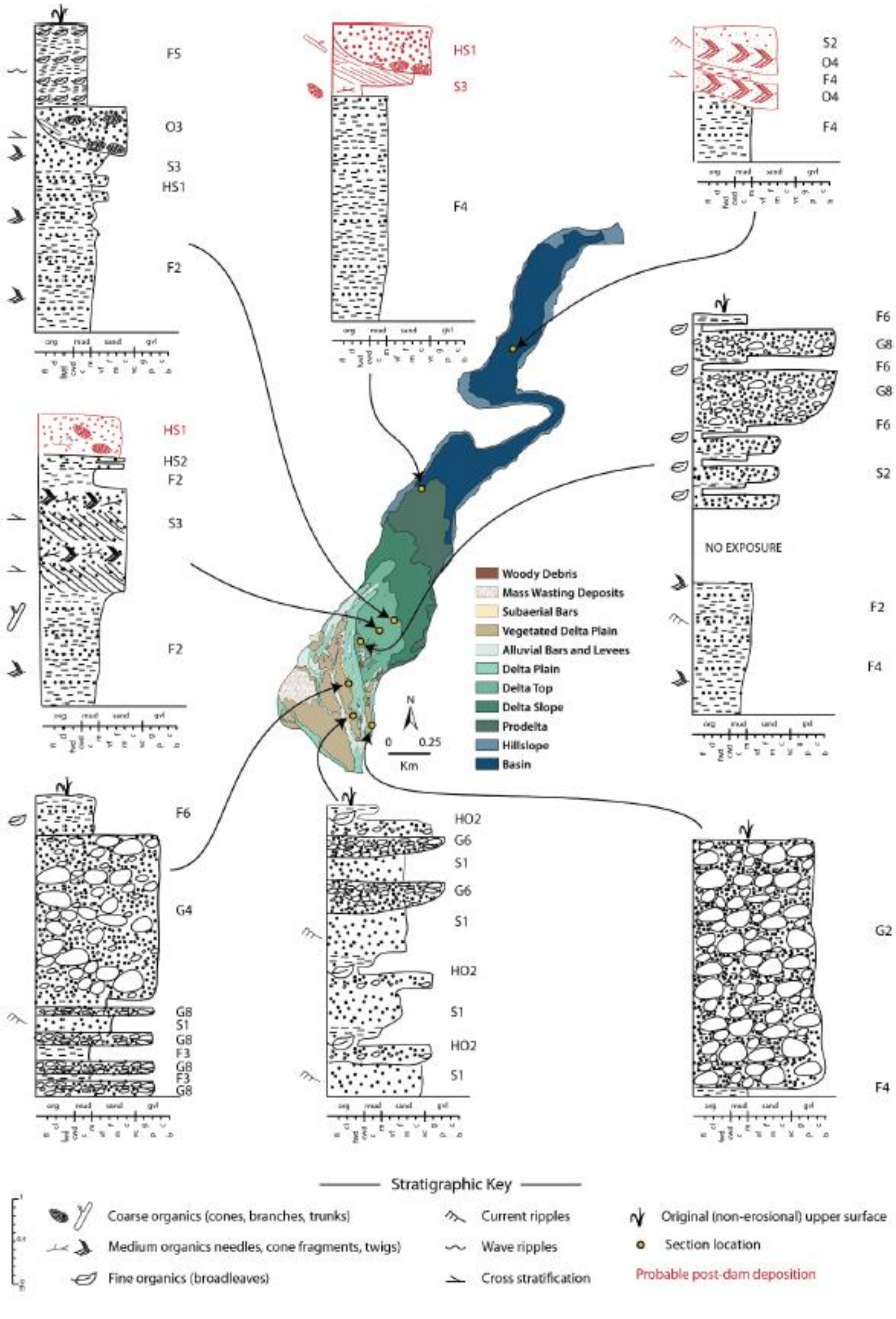


Figure 2-12. Representative stratigraphic sections within geomorphic depositional zones, former Lake Aldwell. Explanation of facies terminology is given in Table 2. Detailed view of geomorphic map given in Figure 6.

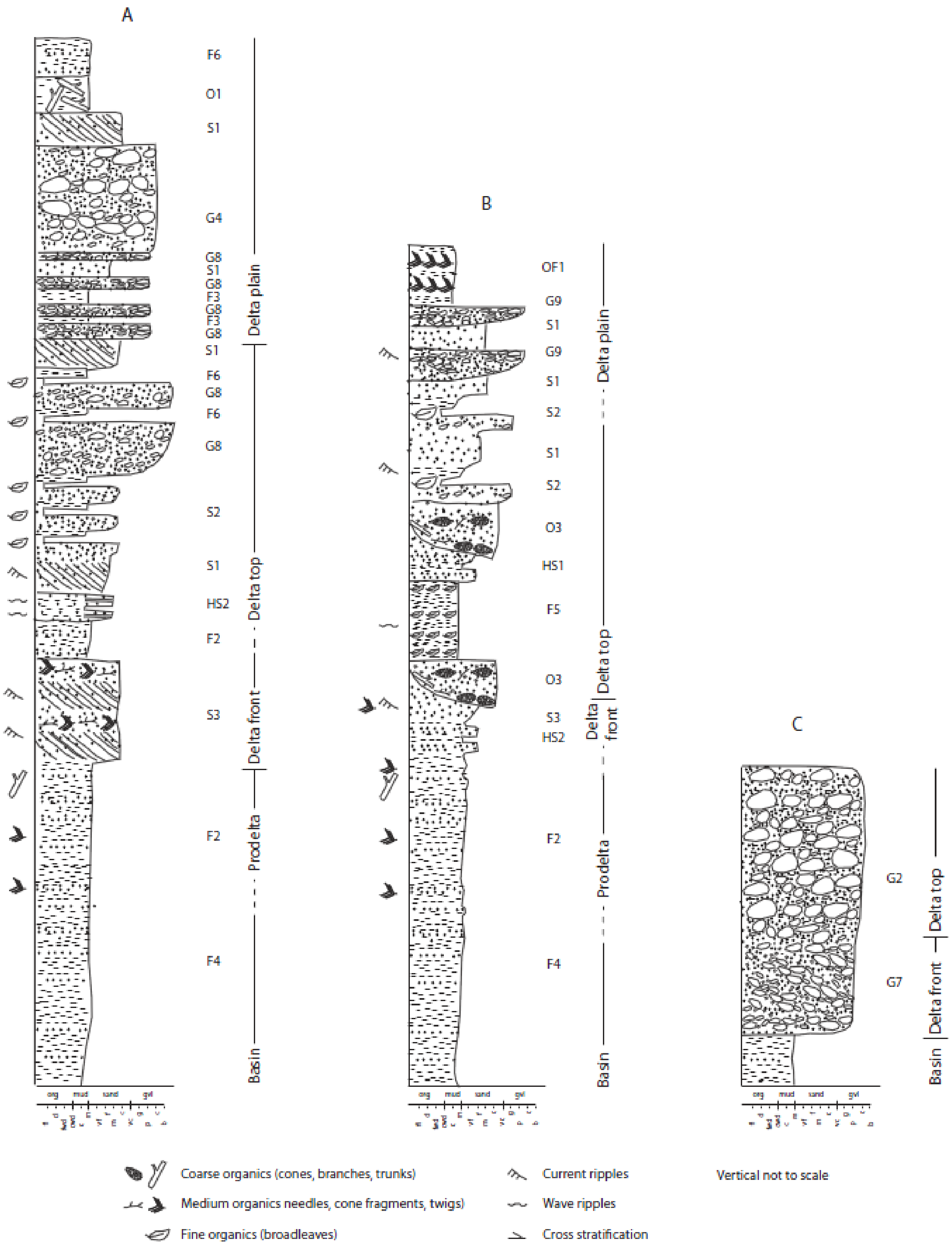


Figure 2-13. Idealized stratigraphic column, former Lake Aldwell. The upper delta plain of former Lake Aldwell was heterogeneous; A) and B) are complete sections likely to occur lower in the basin, while C) represents conditions in the uppermost delta plain.

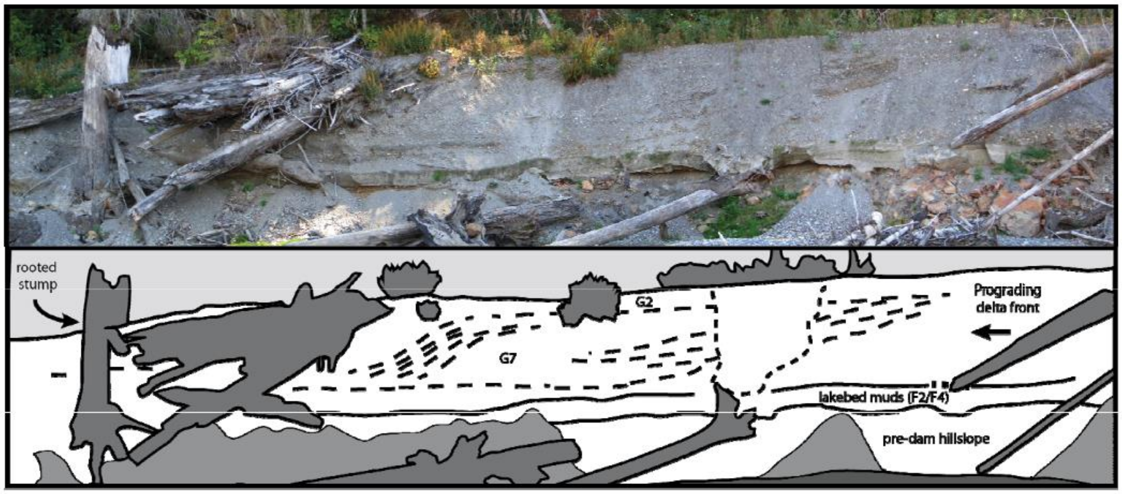


Figure 2-14. Photographic panorama and cartoon showing Gilbert-style progradation in former Lake Aldwell. Flow is to the left.

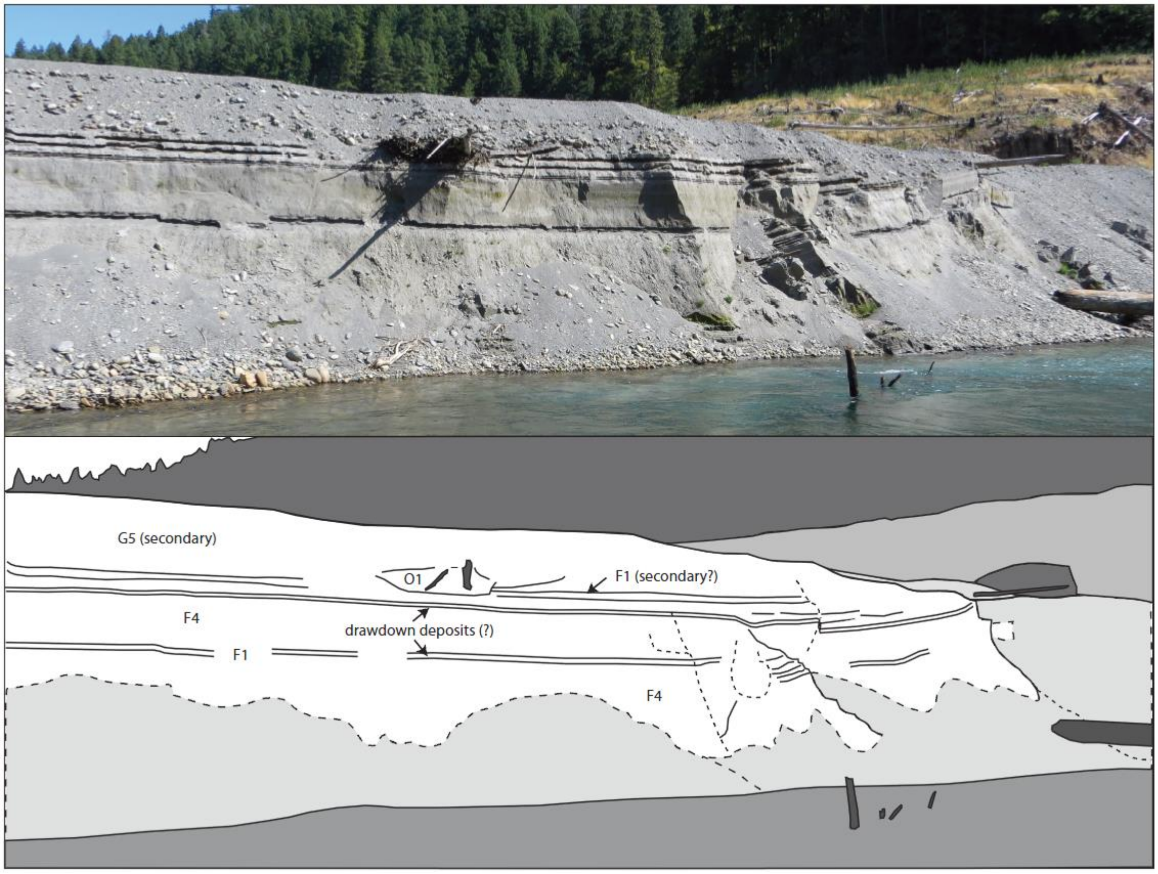


Figure 2-15. Photograph with cartoon depicting sandy interbeds in lacustrine basin of former Lake Mills. Flow is to the left but camera is oriented North along the main axis of the reservoir (toward Glines Canyon Dam).

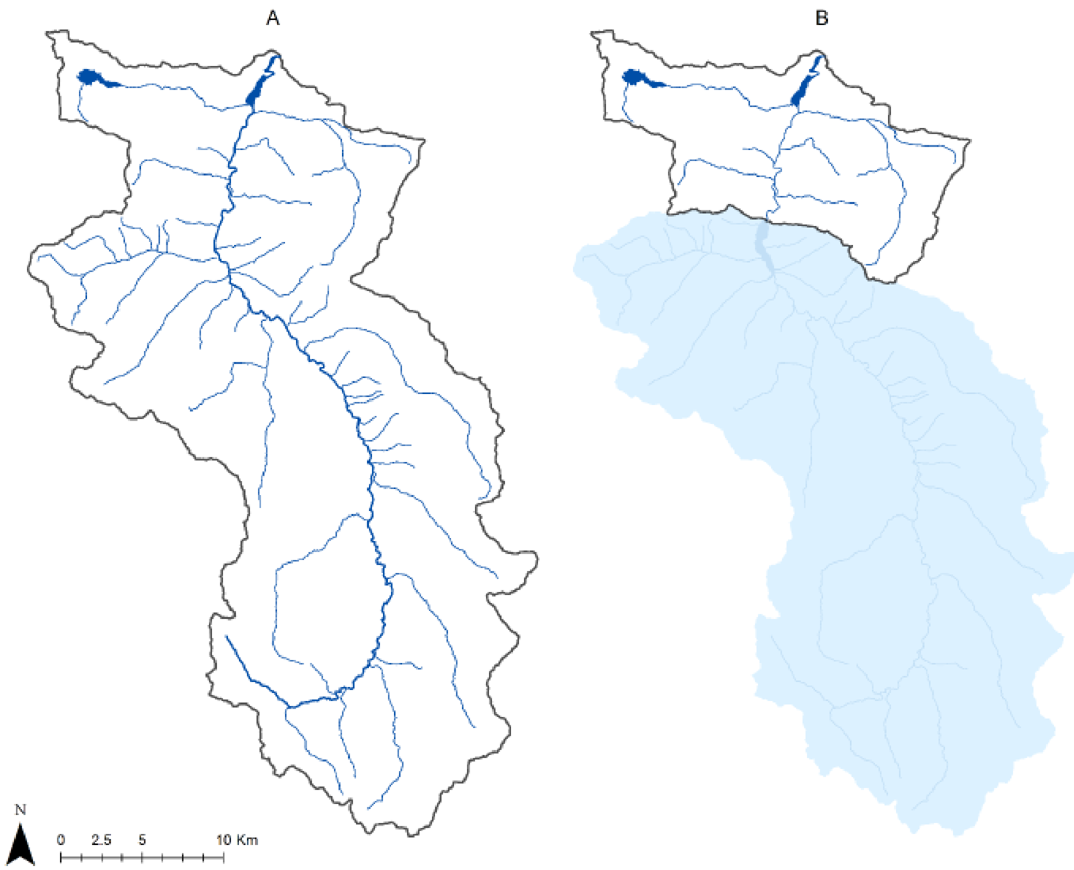


Figure 2-16. Map depicting 78% reduction in bedload source area to Lake Aldwell before (A) vs. after (B) the closure of Glines Canyon Dam (1927).

2.12 Tables

Table 1. Morphological and timeline comparison between former Lakes Aldwell and Mills

Reservoir	Lake Aldwell		Lake Mills	
Dam	Elwha		Glines Canyon	
Dam height (m)	32		64	
Year of closure	1913		1927	
Year of breach	2011		2011-2014	
Inundated river length (m)*	4824		3719	
	YEAR		YEAR	
	1913	2011	1927	2011
Area (m^2)	1.31E+06	1.10E+06	1.82E+06	1.51E+06
Perimeter (m^2)	1.02E+04	2.02E+04	1.08E+04	1.34E+04
Capacity (m^3)†	1.00E+07	5.10E+06	5.12E+07	3.51E+07
Shoreline Development Index§	4.5	9.6	4.0	5.5
Average depth (m)#	7.6	4.6	28.2	23.2
Maximum depth	29	28.5	53	45
Maximum effective length (fetch, m)	2.00E+03	1.20E+03	2.90E+03	2.10E+03
Watershed Area (m^2)	8.15E+08		6.36E+08	
"Bedloadshed" Area (m^2)	8.15E+08	1.79E+08		
Watershed to surface area ratio	620		350	420
"Bedloadshed" to surface area ratio	620	741		

*Calculated as length of estimated former thalweg to end of inundation; estimate for Lake Mills does not include Rica Canyon portion of the reservoir where flow is constrained

†Bountry et al. 2011; Warick et al. 2015. Aldwell capacity does not reflect underestimate of initial capacity as discussed herein

§as D = (L/sqrt(A))

#as volume/surface area; Wetzel 2001

Table 2-1. Morphological and timeline comparison between former Lakes Aldwell and Mills.

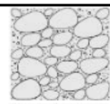
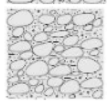
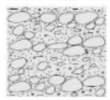
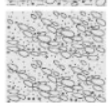
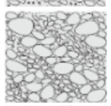
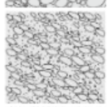
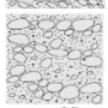
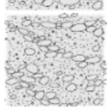
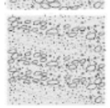
Facies		Description	Bedding	Comments
G1		Unchannelized cobble-boulder gravels; massive to crudely stratified. Clast- to matrix-supported; matrix sandy to pebbly. Little silt.	Sheet-like, laterally extensive beds to 5 m thickness	Frequently associated with Facies O1
G2		Unchannelized, poorly sorted large pebble to cobble gravels; similar to G1 but finer-grained and consistently matrix-supported; some silt in matrix.	Sheet-like, laterally extensive beds to 2 m thickness	More common in Aldwell. Frequently associated with Facies O1.
G3		Matrix-supported, very poorly sorted angular gravels; inverse grading and elevated clasts common.	Subhorizontal to 20° dip, maximum 0.5 m, local unit pinches out downstream	Marginal; minor unit
G4		Weakly graded, weakly channelized silty sandy gravel with lag. Lag shows imbrication, occasional weak channel form.	As multi-story ~0.5 m bed; laterally extensive, pinches out over hundreds of meters	May be clast- or matrix-supported; organics rare.
G5		Cross-stratified, well-imbricated pebble to cobble gravels. Open framework to clast-supported.	Steeply-dipping cross beds 20-30 cm thick; laterally extensive.	Associated with G1; often overlying sheet sands
G6		Interbedded pebble, small cobble, and coarse sand to granule conglomerate. Individual beds moderately to well sorted; may be open framework	Steeply dipping (25-30°) beds to 0.5 m thickness, uniform geometry	Gilbert-style delta foreset; transition to toeset tangential. Associated with O2 and HS3.
G7		Crudely stratified, gently dipping pebble to cobble gravels. Matrix- to clast-supported; little silt.	Forms sigmoidal foreset on scale of 2-3 m; individual beds ~10 cm	Organics rare; where exposed, over-rides Facies F4.
G8		Weakly channelized, well-sorted sandy gravel with prominent lag; little silt. Clast-supported, weakly imbricated to massive. Finer and less silty than G4.	Subhorizontal to broadly undulating; beds 10 cm to 0.5 m thick	Organics rare, but frequently associated with S2 and F6.
G9		Tabular to channelized pebble gravels and pebbly sand. Clast-supported, rarely open-framework. Little to no silt.	Complexly bedded; sheet-like tabular beds cut by channel forms with migration lag	Organics rare. Geometry complex compared to other gravel facies.
G10		Low-angle, tabular pebbly gravel beds interbedded with sigmoidally cross-bedded coarse and very coarse sands. Individual beds to ~1 m thick but pinch out.	Gently dipping to broadly undulatory, laterally extensive but variable.	Organics rare to absent

Table 2-2. Facies designations, former Lakes Aldwell and Mills. Facies are coded by dominant grain size (G = gravel; S = sand; HS = heterogeneous (sandy); F = fines (a field-scale determination including silt and clay); O = organic; OF = organics in fine-grained units or with a fine-grained matrix). Numeric values indicate fining of dominant grainsize within group based on field description (e.g., facies G1 is generally coarser-grained than facies G8 but both are dominated by gravel)

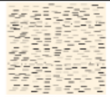
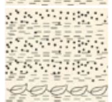
Facies		Description	Bedding	Comments
F4		Thick, massive to weakly laminated blue-gray clayey mud and brown silty mud. Beds to several meters thick.	Subhorizontal, laterally extensive; drapes pre-existing topography.	Major unit; homogeneous. Finer-grained in distal former Lake Mills than Aldwell.
F5		Striped mudstone with fine organics. Silt beds with interlaminated organic mats (mostly leaves). Interbeds 1 to 3 cm, weakly wavy to planar	To 2 m total thickness, subhorizontal, laterally extensive	Organic interlamina well preserved, well-sorted broadleaves
F6		Thinly graded fine organic and silt interbeds with fine sand. Sticks, cones, and bark fragments constitute minor total area of unit but are not uncommon.	Subhorizontal; laterally extensive	Often interbedded with gravels.
F7		Poorly sorted, thick-bedded silty sand to sandy silt capped by silt bed. Chaotic fabric with occasional climbing ripples and organics.	Variable, frequently erosive. Laterally extensive.	Similar to S4 but finer grained. Appears to be drawdown-exclusive unit.
F8		Laterally-migrating, channelized mud-clast conglomerate interbedded with pebbles, sands.	Laterally-migrating channel form directly overlying forest floor	Rare; probably drawdown-only unit
O1		Interlocked, randomly-oriented branches to 2-3 cm diameter forming open-framework lenses or beds. Sticks typically bark-denuded but angular.	Channelized lenses or planar beds pinching out within several meters	Typically associated with gravel facies; isolated but not uncommon.
O2		Steeply dipping, well-bedded organics including branches, cones. 'Clast'- to matrix-supported, matrix medium sand and granules.	Steeply dipping (25-30°), to 1 m thick	Prominent in foreset beds. Organics well preserved.
O3		Clast-supported medium to coarse organics in a sandy matrix with common muddy interbeds. Fabric typically chaotic; organics may occur as lag.	Undulating channel form or as lenses; bottom contact typically erosional.	Common in former Lake Aldwell
O4		Cross stratified to cross-bedded channelized organic units in sandy matrix. Clast to matrix supported; organics are needles, bark fragments, cones.	Gently dipping or subhorizontal, channel cuts common	Appears to be drawdown-exclusive unit
OF1		Weakly bedded silt and organic unit. Organic units matrix supported, densely packed, silty matrix to open framework	Beds 1 cm to 10 cm thick, subhorizontal to undulating.	Upper contact shallow or subaerial at time of exposure

Table 2-2 (continued). Facies designations, former Lakes Aldwell and Mills. Facies are coded by dominant grain size (G = gravel; S = sand; HS = heterogeneous (sandy); F = fines (a field-scale determination including silt and clay); O = organic; OF = organics in fine-grained units or with a fine-grained matrix). Numeric values indicate fining of dominant grainsize within group based on field description (e.g., facies G1 is generally coarser-grained than facies G8 but both are dominated by gravel)

Facies		Description	Bedding	Comments
OF2		Coarse organics (branches to 10 cm diameter, sticks, root balls) in mud matrix. Tightly packed, clast-supported	Irregular; often in lee of stranded root ball	Discontinuous; isolated within other facies

Table 2-2 (continued). Facies designations, former Lakes Aldwell and Mills. Facies are coded by dominant grain size (G = gravel; S = sand; HS = heterogeneous (sandy); F = fines (a field-scale determination including silt and clay); O = organic; OF = organics in fine-grained units or with a fine-grained matrix). Numeric values indicate fining of dominant grainsize within group based on field description (e.g., facies G1 is generally coarser-grained than facies G8 but both are dominated by gravel)

2.13 Supplementary Information

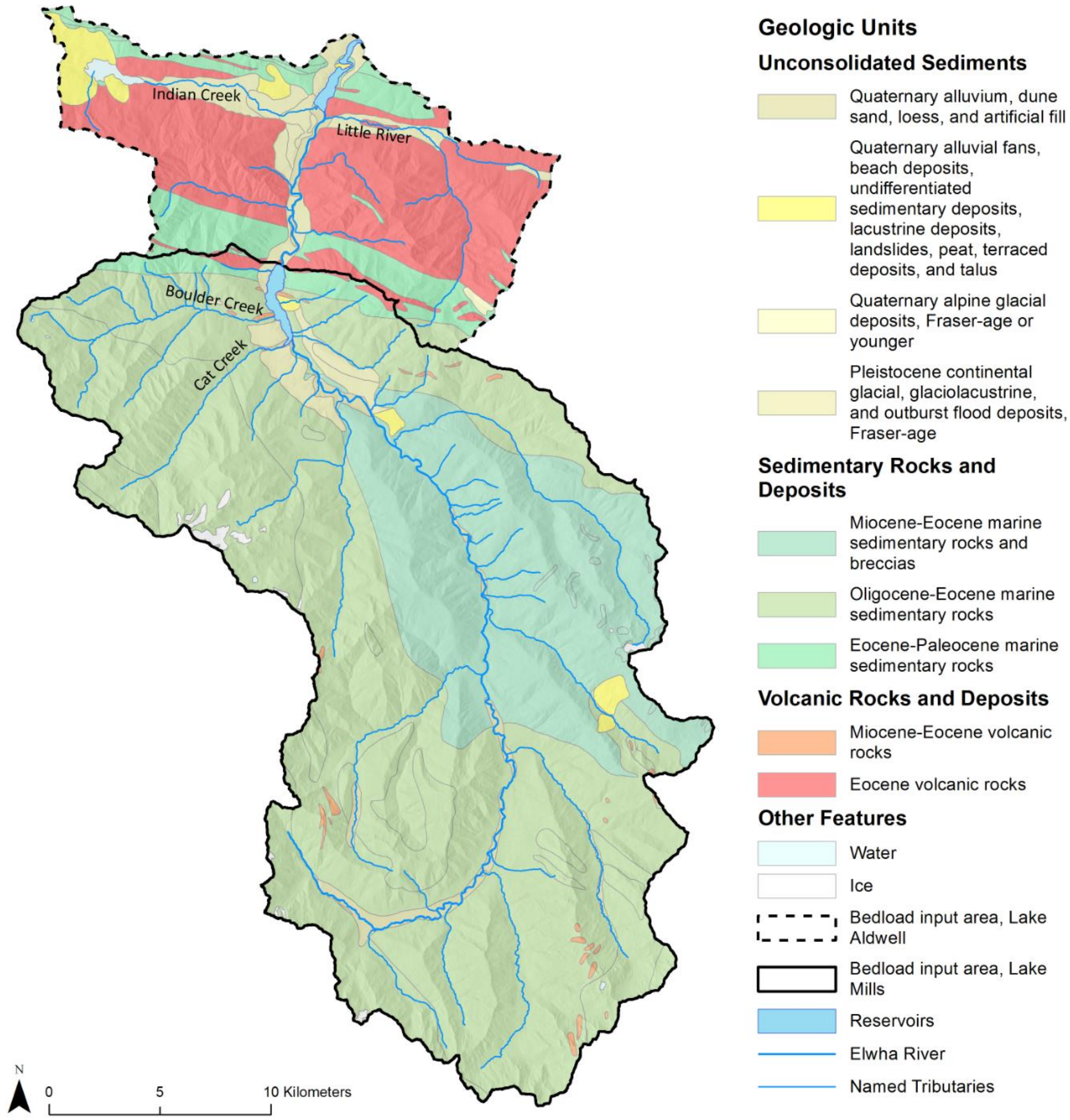


Figure SI-2-1. Geology of the Elwha catchment depicting named tributaries to Lakes Aldwell and Mills. Geologic data after Schuster, 2005.

3 Stratigraphic-Based Analysis of Organic Matter Deposition in Two Former Hydropower Reservoirs: The Importance of Coarse Organic Matter to Carbon Loads and Burial in Artificial Impoundments in Mountainous Environments

Laurel E. Stratton, Roy Haggerty, and Gordon E. Grant

For submission to *Limnology and Oceanography*

3.1 Abstract

The relationship between carbon burial and sedimentation in reservoirs is unknown, contributing to uncertainty in our understanding of the net impact of dams to the global carbon budget and exposing gaps in our fundamental understanding of the transport, processing, and deposition of organic matter in fluvial and lacustrine systems. Taking opportunistic advantage of the removal of two high-head dams in Washington State, USA, we investigate this relationship by developing a stratigraphic, process-based framework to estimate total carbon accumulation as a function of depositional environment in the sediments of two former ~1 km^2 reservoirs on the Elwha River. Former Lake Mills (upstream; completed 1927) accumulated ~330 Gg of, with depositional-zone average accumulation rates from 229 to 9262 $gCm^{-2}yr^{-1}$, while Former Lake Aldwell (downstream; completed 1913) accumulated ~ 91 Gg (263 to 2414 $gCm^{-2}yr^{-1}$). Carbon storage in both reservoirs was dominated by heterogeneous, coarse organic matter and woody debris in the coarse-grained delta slope and relatively coarse-grained prodelta regions of the reservoirs, with little storage in the gravel-dominated, subaerial delta plains. Carbon accumulation in fine-grained lacustrine and prodelta sediments was relatively homogeneous, but turbidity flows from the Gilbert-style delta slope in former Lake Mills delivered significantly more carbon to the prodelta than the mouth-bar style delta of former Lake Aldwell. C:N ratios support interpretation of most organic matter in both reservoirs as allochthonous. Sampling schemes based only on lacustrine and/or prodelta would underestimate of total carbon accumulation by up to 30% in former Lake Aldwell, but the overestimate by up to 47% in former Lake Mills.

3.2 Introduction: carbon accumulation in reservoirs

The widespread construction of large (>15 m) dams over the last century has altered the fluvial connections between terrestrial and oceanic environments on a global scale. Conservatively, dams and reservoirs now affect ~50% of large rivers (Nilsson et al. 2005; Lehner et al. 2011), intercept > 40% of global discharge (Vörösmarty et al. 2003) and have increased the global terrestrial water surface by >7% and the lacustrine freshwater storage by ~10% (Gleick, 2000). As a result, as much as 25% of global annual sediment discharge is now impounded (Vörösmarty et al., 2003), resulting in a 1400 Tg yr^{-1}

decrease in global sediment delivery to oceans despite an estimated 2300 Tg yr^{-1} anthropogenic *increase* in global sediment transport (Syvitski et al., 2005). Indeed, a provocative recent paper argues that sediment retention behind dams is a fundamental marker of the stratigraphic and functional distinctiveness of the Anthropocene (Waters et al., 2016).

A small but significant portion of sediment retained behind dams is composed of organic carbon. Reservoirs, which tend to be located on high order streams with large, variably degraded watersheds, typically receive significant allochthonous organic matter input (Renwick et al. 2005; Jacinthe et al., 2012; Maavara et al., 2017). Similarly, high nutrient loads in incoming waters tend to produce eutrophic reservoir conditions with high autochthonous production levels as compared to lakes (Wetzel, 2001; Jacinthe et al., 2012; Clow et al., 2015). While much of this organic matter is mineralized and emitted to the atmosphere as carbon dioxide (CO_2) and methane (CH_4), much of it is buried in reservoir sediments (Cole et al., 2007; Mendonça et al., 2012; Maavara et al., 2017). Emission of greenhouse gases from reservoirs has been the subject of intensive study and debate over the last several decades (cf. Deemer et al., 2016); however, complementary studies of carbon burial are relatively scarce and estimates of burial rates vary widely. As a result, the net impact of damming to the global carbon cycle remains unknown.

A recent, comprehensive effort to estimate total carbon burial in lakes and reservoirs of the conterminous United States states that “national-scale assessments of [organic carbon] (OC) burial in… reservoirs have been based on sparse data sets from disparate sources," before noting that the databases from which their own data are drawn represent less than 1% of reservoirs in the conterminous United States (Clow et al, 2015; p. 7615). Commonly cited estimates of area-weighted carbon burial in reservoir systems vary by up to three orders of magnitude (e.g., Mulholland & Elwood, 1982; Dean & Gorham, 1998; Stallard, 1998; Downing et al., 2008), while recent estimates of total global carbon burial in reservoir sediments are an order of magnitude lower than suggested by previous studies (Mendonça et al., 2017; Maavara et al., 2017).

The uncertainty in global estimates is compounded by uncertainty in local-scale estimates derived from individual reservoirs. In contrast to the ‘depocenter’ paradigm of homogeneous deposition in lakes, reservoirs are dynamic systems with complex processes influencing sediment transport and deposition (c.f. Shotbolt et al., 2005). Intra-reservoir sedimentation has been shown to vary with watershed characteristics, such as land use and geologic provenance, among different tributaries (Viseras et al., 2009), as well as key processes, including deltaic fallout (Snyder et al., 2004), turbidity currents (Kostic et al., 2002; Twichell et al., 2005; Wildman et al., 2011; Kunz et al., 2011), and reservoir operational regimes (Keith et al., 2016), all of which can vary spatially and temporally (cf. Mulholland and Elwood, 1982; Thornton et al. 1990; Morris and Fan, 1998; Abraham et al., 1999; Ambers, 2001; Pondell and Canuel, 2017; Stratton et al., in press).

Because of this complexity, few studies have explicitly addressed the spatial or temporal variability of carbon burial as a component of sediment deposition; those that have report widely varying depositional patterns. Vanni et al. (2011) found that, based on a longitudinal core transect, average organic carbon concentration increased downstream in two hard-water reservoirs in the state of Ohio. In contrast, Mendonça et al. (2016) found that organic carbon concentration *decreased* downstream in a subtropical reservoir in Brazil. In Lake Kariba, Zimbabwe, Kunz et al. (2011) used varved sediments to determine that flood layers were distinct from background sedimentation and that sedimentation style and carbon concentration varied between the buried river thalweg and 'littoral' sedimentation in areas outside the influence of thalweg-constrained density currents. In contrast, Pondell and Canuel (2017) found that heterogeneity in reservoir sediments was primarily expressed in the deltaic portion of a reservoir in northern California, with average carbon concentration decreasing with distance from the reservoir inflow. This variability suggests that, as noted by Mendonça et al. (2016), the relationship between carbon burial and complex patterns of sedimentation is generally unknown. This gap creates uncertainty in our estimates and understanding of the net impact of dams on the global carbon budget and reveals deficiencies in our fundamental understanding of the transport, processing, and deposition of organic matter in fluvial and lacustrine environments.

We capitalize on a unique opportunity created by the 2011-2014 removal of two large dams on the Elwha River, Washington, USA to investigate the spatial and temporal dynamics of organic matter deposition and storage in two former reservoirs. The removal of Elwha and Glines Canyon Dams from the Elwha River is the largest dam removal project yet completed globally (Randle et al., 2015). The scale and pioneering nature of the project attracted the notice of scientific researchers nationwide, who completed a wide variety of investigations related to fish passage, river adjustment, ecological succession, policy implications (c.f. Duda et al., 2008, *Geomorphology* v. 246), and reservoir sediment stratigraphy (Stratton et al., in press). These studies range over a period of more than 20 years and required the collection of extensive, diverse datasets to properly engineer the dam removal, manage sediment excavation, and monitor river adjustment.

Here, we synthesize a wide variety of these data with our own field-based observations to develop a coherent narrative of the dynamics of carbon burial in the sediments of former Lakes Aldwell and Mills. These data sets include: grain size analysis completed in the 1990s as part of the original removal planning process (Gilbert and Link, 1995), volumes modeled using surveys completed prior to dam removal (Bountry et al., 2011), grid-based analytical samples of total carbon and nitrogen concentrations in reservoir sediments collected during the summer of 2013 (midway through the removal process) (Wing, 2014), and in-situ stratigraphic analysis completed during the summer of 2014 (Stratton et al., in press). By analyzing patterns of deposition, sediment yield, and relative carbon and nitrogen volumes, we investigate three questions necessary to understanding the deposition of carbon in reservoir sediments: First, where is carbon stored in reservoirs and what processes contributed to its deposition? Second, what is the primary source of carbon in reservoir sediments and how does it vary between and within individual reservoirs? And third, what can these insights tell us about the total volume of carbon accumulation in reservoirs?

Stratigraphy and sediment analysis have long provided a paradigm to recognize patterns and interpret the processes responsible for carbon storage in both terrestrial and aquatic environments (c.f. Huc, 1990). However, this work is unique in its application of stratigraphic tools to better understand carbon burial in the sediments of artificial reservoirs; additionally, by coupling stratigraphic tools to a geomorphic perspective, this study develops a process-based approach to characterize the deposition and storage of carbon in reservoir sediments. While the resulting estimates of total carbon burial in former Lakes Aldwell and Mills are inevitably case-specific, the stratigraphic approach and process-based understanding developed here are broadly applicable to a wide range of reservoir environments, informing both better volumetric estimates of carbon storage worldwide and a better understanding of the controls influencing organic matter transport, deposition, and long-term storage in aquatic environments.

3.3 Study Area

3.3.1 Elwha Watershed

Detailed background on the Elwha River watershed is provided in Duda et al. (2008). In brief, the Elwha River watershed comprises 833 km^2 on the northernmost Olympic Peninsula (Figure 1), draining the glaciated Olympic Mountains north to the Strait of Juan de Fuca. Precipitation is strongly seasonal and shows a sharp orographic gradient over the watershed; annual peak discharges on the Elwha River occur in winter with a secondary peak during spring melt out. Average daily discharge is ~43 m^3/s and the flood of record (recorded in 1897) is 1180 m^3/s, with seven measured annual peak discharges in excess of 800 m^3/s since 1897 (Duda et al., 2008).

Sediment sources in the Elwha drainage are abundant due to the steep gradient, highly erodible bedrock, and history of glaciation in the watershed (Tabor and Cady, 1978; Tabor, 1982; Brandon et al., 1998; Batt et al., 2001; Schuster, 2005; Acker et al., 2008; McNulty 2009; Draut et al., 2011). However, sediment delivery to channels is moderated by thick forest and other vegetative cover and very limited land use development as the result of long-standing federal protection of most of the watershed (NPS, 1996). Studies on plant communities completed in the vicinities of Lakes Aldwell and Mills found 90% of land area was vegetated; of the remaining 10% land area, 80% was composed of the river itself and associated gravel bars (NPS, 1996). Plant communities are dominated by conifer forest (43%; predominantly western hemlock and Douglas fir), mixed forest (18%), hardwood forest (17%), and palustrine forest (6%), with minor areas of grassland, deciduous shrubs, and low wetland communities (NPS, 1996).

Water quality on the Elwha is unusually pristine for a reservoir system. As measured at the McDonald Bridge gage, located at RM 8.6, immediately upstream of former Lake Aldwell, dissolved oxygen, total nitrogen, and total phosphorous values in Elwha River water are consistent with waters typically classified as oligotrophic (FERC, 1991; Wetzel, 2001). Additionally, water quality data collected from Lakes Aldwell and Mills in the summer and early fall of 1987 indicated pH and alkalinity values typically associated with oligotrophic systems, and dissolved oxygen and secchi depth readings typically considered oligotrophic to mesotrophic (FERC 1991; Wetzel, 2001). No direct measurements of in-reservoir productivity were apparently ever collected; however, low nutrient values are typically associated with limitations on algae growth (Wetzel, 2001).

3.3.2 Elwha Reservoirs

Elwha Dam was completed in 1913 and impounded Lake Aldwell until 2011. Glines Canyon Dam, located approximately 18 km upstream, was completed in 1927 and impounded Lake Mills until 2012. Elwha Dam was 33 m tall and impounded a reservoir 1.3 km^2; as described in Stratton et al. (submitted), former Lake Aldwell had an initial water capacity of approximately 1.0×10^7 m^3, an average depth of 7.6 m, a maximum depth of 29 m, and maximum fetch of 2,000 m. Glines Canyon Dam was 64 m tall and impounded a reservoir with similar area but five times the capacity of former Lake Aldwell. During the decades the dams impounded the Elwha, the river built substantial deltas into both former reservoirs, significantly reducing their capacity, area, and average depth while increasing the shoreline complexity (Stratton et al., submitted).

The dams were operated primarily as “run of the river”, i.e., constant head, facilities from at least 1975 onward (NPS, 1996; Duda et al., 2008). To restore native fish populations reduced by 90% from their pre-dam abundance, both dams were removed from 2011 to 2014 (Pess et al. 2008; Duda et al. 2008). Removal occurred in stages, during which each reservoir was drawn down by a depth of 3 to 5 m and held at that elevation for a period of time before proceeding to the next step (Randle et al., 2015). This process allowed time for the Elwha River to erode significant portions of the deltaic deposits through incision and lateral migration at each step, creating terraces with extensive cutbank exposures and the opportunity for detailed stratigraphic study.

3.4 Methods

We previously developed a stratigraphic model for former Lakes Aldwell and Mills based on 100+ surface and cross-sectional exposures in the former reservoirs (Figure 2) (Stratton et al., in press). The facies defined here (Table 1) use the same designations as those in that study, but are expanded to more rigorously describe and categorize the observed organic detritus (see supplementary information). Facies are coded by dominant grain size (G = gravel; S = sand; HS = heterogeneous (sandy); F = fines (a field-scale determination including silt and clay); O = organic; OF = organics in fine-grained units or with a fine-grained matrix) and grain size within the group, from coarse to fine (e.g., G1 is coarser than G2 but both are gravel-dominated). "Organic" facies (those designated "O" or "OF" consist of units that, at the facies scale, are 50% or greater organic matter by visual estimation of area or for which organic components provide the clastic framework.

Analytical data is from Wing (2014). Samples were collected by defining 390-m north-south transect intervals and selecting three to five plot locations along each transect (Figure 2). At each plot, samples were collected at intervals from 0 to 20 cm, 20 to 50 cm, 50 to 100 cm, and at subsequent one meter intervals as deep as feasibly possible to the total depth of sediment accumulation. Maximum sampling depth was 600 cm. Samples were collected using a variety of soil coring probes and with sharp-pointed trowels, depending on conditions. Samples were analyzed to determine total organic content (TOC), carbon to nitrogen (C:N) ratios, bulk density, and coarse (>2 mm) vs. fine fraction (≤2 mm) according to the methodology detailed in Wing (2014). C:N ratios are reported as weight ratio; and can be converted to molar ratio by multiplying by the molecular weight ratio (14/12 or 1.67).

Using location, adjacent stratigraphic sections, and plot and sample photographs, we classified individual analytical samples according to 1) depositional era, 2) depositional zone, and, where possible, 3) facies. Depositional era includes 1) predam (i.e., soils deposited prior to the establishment of the reservoirs), 2) primary (i.e., sediments deposited during the normal operating lifespan of the former reservoirs), and 3) secondary (i.e., sediments deposited during dam removal-related drawdown events. Depositional zones and facies are discussed below. Statistical analysis of analytical samples was completed using R version 3.0.3. Standard error was measured using a one-sample t- test (p values reported below) and comparison of means using a two-sample t-test (p values reported below).

Volume and area calculations were completed using ArcMap 10.3.1 Spatial Analyst functions on 3.048-m^2 horizontal resolution digital elevations models (DEMs) provided by the US Bureau of Reclamation (Bountry et al., 2011). DEMs representing pre-dam surface elevations in former Lake Mills are based on 1.52-m (5-ft) topographic maps completed prior to dam construction. No such map was completed for former Lake Aldwell; as a result, the pre-dam river thalweg was estimated using contemporaneous photographs and large-scale maps. Estimated uncertainty in volumetric calculations is 13% for former Lake Mills and 26% for former Lake Aldwell. We digitized the approximate reservoir outlines in the earliest available maps or aerial photographs of each reservoir and subdivided the reservoir into depositional areas as mapped in Stratton et al. (submitted), then performed simple raster subtraction to determine the volume of sediment accumulated in each depositional zone.

Grain size distributions are from Gilbert and Link (1995), who utilized a depositional-zone based approach to quantify sediments and sediment grain size in both former reservoirs as part of early dam removal planning (see supplementary information). These areas were based on average sampled grain size and are thus not directly comparable to the depositional zones in this study, but provide estimates of grain size and simple facies architecture from a similar environment-based perspective.

3.5 Results

3.5.1 A stratigraphic approach to the deposition of organic matter

To understand where carbon is stored in reservoir sediments and the processes that contributed to its deposition, we combine the facies-based conceptual model of Stratton et al. (submitted), which divided the former Lakes Mills and Aldwell into depositional zones characterized by similar facies architecture, depositional processes, and morphology, with descriptive stratigraphic analysis of visible detrital organics and analytical results from Wing (2014). Composite stratigraphic columns (Figure 3) depict facies typical of each depositional zone within the reservoir, while analytical values for each facies sampled by Wing (2014), combined with other literature values, are used to develop average TOC and C:N values for each facies type (Table 2; Figure 4a) and depositional zone (Table 3).

3.5.1.1 Lake Mills

As discussed in Stratton et al. (submitted), former Lake Mills was characterized by a classic Gilbert-style delta (Gilbert, 1885). Gilbert deltas are typical of flow into non-saline, relatively deep-water basins, where the abrupt expansion of flow and decrease in gradient, combined with homopycnal conditions, causes an abrupt loss of competence and the deposition of bedload (c.f. Bates, 1953; Wright, 1977). The resulting delta deposit is typically defined by a tripartite structure, consisting of coarse-grained, low-angle topset beds, coarse-grained, steeply-dipping foreset beds, and low-angle, fine-grained bottomset beds, beyond which are lacustrine-style deposits (Figure 3a). As the delta progrades into the water body, the result is a coarsening-upward stratigraphic section diagnostic of deltaic conditions. Here, we describe the deposits of former Lake Mills longitudinally from the inflow of the Elwha River to the dam.

3.5.1.1.1 Delta plain and delta top

By 2010, when a detailed survey of reservoir sediments was conducted (Bountry et al., 2011), the Elwha River had built a subaerial or nearly subaerial delta nearly 1 km into the reservoir from the mouth of Rica Canyon (Figure 2). The delta plain and delta top depositional zones of former Lake Mills (Figure 2) represent a large number of complex environments, but are probably volumetrically-dominated by gravel topset beds. Complete exposures near Boulder Creek, Cat Creek, and the mouth of Rica Canyon (Figure 2) show multi-story accumulations of the coarse-grained G1, G5, and O1 facies (Table 1; Figure 3a), while fluvial gravels and finer-grained facies indicative of alluvial environments appear to be limited to relatively thin veneers at about the former normal operating water surface elevation. This supposition is supported by grain size analysis of topset units, Rica Canyon sediments, and the Cat Creek Fan collected in 1994, which were measured to contain <5% silt and <10% fine sand (Gilbert & Link, 1995). Downstream of the subaerial delta plain, the delta top in former Lake Mills at the time of dam removal was a relatively small area of subaqueous mouth bar sands representing the zone of active deposition at the delta front, which appears to have developed as the result of basin shallowing due to interactions with the Boulder Creek delta but was poorly preserved during dam removal (Stratton et al., submitted).

Organic matter deposition in the delta plain and delta slope of former Lake Mills was extremely heterogeneous, making volumetric estimates of total carbon content difficult. As measured by Wing (2014), sediments in the G1 facies in former Lake Mills are negligible, with an average wt% TOC of 0.34 ± 0.08 (Table 2). However, irregularly-occurring organic lenses in the delta plain and delta top depositional areas form discrete organic-rich, pockets. These organic-rich units consisted primarily of the O1 facies, characterized by fine woody debris forming open-framework lenses, and the O3 facies, a clast-supported unit comprised of needles, general litter, and fine woody debris typically observed in discrete lenses or with an undulating channel form that pinches out downstream (Table 1). Other occurrences of organic matter in topset deposits consisted of stranded coarse woody debris ranging from root balls and single trees to large rafts of interlocked coarse woody debris (for example, at the uppermost head of the delta plain; Stratton et al., submitted); these occur both at the surface and interbedded with the G1 and G4 facies (a minor, finer-grained gravel facies).

The importance of coarse organic facies like O1 and O3 and storage of coarse woody debris to the overall carbon storage of the system is difficult to quantify. Wing (2014) did not collect samples representative of the O1 or O3 facies; however, O4, a secondary (i.e., dam removal-related) deposit similar to O3 was measured with a wt% TOC of 12.77. Additionally, samples of coarse organic matter-dominated sediments collected from other systems have been measured in excess of 30 wt% TOC (e.g., Pondell and Canuel, 2017; Stratton, unpublished data). These concentrations suggest that, despite their limited volume and irregular distribution, organic-rich lenses in the coarse-grained topset beds of former Lake Mills store significant volumes of carbon.

3.5.1.1.2 Delta slope

While most coarse woody debris appears to have been confined to the delta plain, organic matter preserved downstream in the delta slope (foreset beds) and prodelta regions (Figure 2) contained prominent accumulations of fine woody debris, litter, and even occasional instances of large woody debris. Characteristic facies in the delta slope foreset and toeset beds included S3, O1, O2, G3, G6, G10, HS2, and HS3 (Table 1; Figure 3), all of which, with the exception of the gravels, tend to be rich in visible detrital organics. The O1 and O2 units are similar, composed of interlocked, randomly-oriented branches to 2-3 cm diameter and 50 to 100 cm long, but indicative of different environments. The O1 facies tended to occur as toeset runout and often shows evidence of winnowing, while the O2 facies occurs as steeply dipping foreset beds as much as 1 m thick. Often the O2 facies appears to cap a single, well-sorted sand bed, probably representing foreset progradation by flood event. In the O2 facies, clasts of woody debris are typically well-imbricated and intact to well-preserved, suggesting transport in traction but over relatively short distances; the O2 unit tends to be coarser than the O1 and to be complexly interbedded with sand and gravels. HS (for 'heterogeneous, sand-based') facies are finer grained and for the most part preserve needles and leaves in the lee of cross-lamina. Beds to 5 cm thick of imbricated, well-preserved leaves occur throughout but represent a minor over-all component of the facies (10% surface exposure or less).

With the exception of the Boulder Creek delta, the foreset beds in former Lake Mills were almost entirely excavated during the reservoir drawdown (although their pervasive presence in the delta was noted during a drawdown experiment documented by Childers et al. [2000] and anecdotally by scientists monitoring the early days of the dam removal [Bountry, personal communication]). As a result, no data exist for the average organic content of the delta slope in former Lake Mills; however, data from Englebright Lake provides clues to the carbon load in former Lake Mill's delta slope. Core samples collected from the foreset beds of Englebright Lake appear to be strongly influenced by event-based sedimentation, with relatively fine-grained, background sedimentation averaging 0.9 ± 0.8 wt% TOC and distinct sandy units capped by organic detritus averaging 15 to 32 wt% TOC. This event-based interpretation is in keeping with data from the toeset/proximal prodelta beds of Lake Billy Chinook, a Gilbert delta-dominated reservoir on the Deschutes River, Oregon (USA) discussed further below (Stratton, unpublished data), and with the stratigraphic heterogeneity visible in exposures in former Lake Mills. Pondell and Canuel (2017) measured the average wt% TOC in Englebright Lake, including both background and event-based deposition, as 2.64 ± 5.95.

3.5.1.1.3 Prodelta

Downstream of the delta slope, Lake Mills was characterized by thick accumulations of organic-rich prodelta sands, designated the S3 facies (Figure 3). These sands were frequently interbedded with the F1 facies (discussed below) and with organic-rich facies O1 and HS2. The S3 facies is typically characterized by multi-story, 10- to 50-cm beds of well-sorted fine to medium sand, typically showing planar to sigmoidal cross lamina and climbing ripples. Detrital organics may be absent or occur in two forms: 1) as dispersed clasts (typically intact to well-preserved conifer needles; more rarely, as cm-scale leaf fragments) trapped in the lee of current and climbing ripples or as interlamina within sigmoidal cross bedding and, 2) as ≤4 cm interbeds composed of intact to well-preserved general litter and fine woody debris. These beds appear to cap the underlying individual sand beds and are frequently clast-supported to open framework. Closer to the delta toeset, the organic interbeds may reach 10 cm thickness and extend for tens of meters.

In samples collected from the Elwha reservoirs, the S3 facies has an average TOC of 2.19 ± 3.16 wt%. The large variance, while possibly reflective of the small sample number (n = 4) is more probably reflective of real heterogeneity within the unit at a scale difficult to capture in analytical samples, as in Englebright Lake, discussed above. Of S3 samples collected from the former Elwha reservoirs, the reported TOC content ranges from 0.36 wt% to 5.02 wt%, reflecting the difference in carbon content between clean sand interbeds and those characterized by conifer needles and other detrital carbon. In organic-dominated beds, 5 wt% TOC is probably an underestimate. Samples collected from the proximal prodelta in Lake Billy Chinook, a large reservoir characterized by subaqueous Gilbert-style deltas, have similar stratigraphy to the Elwha dams’ transition from F1 to S3 facies and report average TOC of 2.81 ± 1.64 wt% and 4.51 ± 1.18 on two major arms (Stratton, unpublished data).

With increasing distance from the delta, prodelta sands were more frequently interbedded with the F1 and F2 facies (Figure 3). Occupying the longitudinal axis of the prodelta, the F1 facies was comprised of ≥50% fine sand interbeds (to 15 cm thick) that formed a distinctive “striped mudstone” appearance and was extensive across the proximal prodelta area. Organics in the fine-grained lamina of the F1 facies tend to occur as 1 mm to 1 cm lamina of well- to poorly-preserved general litter and well-preserved needles in the lee of ripples. The sandy interbeds tend to be devoid of visible detrital carbon with the exception of discontinuous lenses of intact needles stranded in the lee and trough of current ripples, which, while visually prominent, do not appear to constitute a significant fraction of the sediment accumulation. This concentration of needles in ripple troughs is consistent with descriptions by Gastaldo (1994), who note that the mesodetrital fraction of organic matter often “behaves sedimentologically in a manner similar to that of mica....dispersed across the bedding surface or concentrated in ripple troughs.” (p. 115). TOC content for the F1 facies is 1.26 ± 0.23 wt%.

Occurring distally and marginally, the F2 facies represents the transition from purely suspended-sediment deposition in the basin to zones within the reservoir occasionally influenced by distal turbidity current outflow (Stratton et al., submitted). Within the F2 facies, organic interlamina are increasingly common with proximity to the delta, occurring as 1 mm to 1 cm lamina of well- to poorly-preserved general litter and well-preserved needles in the lee of ripples. In addition, F2 deposits in the prodelta are occasionally interrupted by lenses or channelized units of chaotically-bedded needles, general litter, and fine woody debris in a matrix of poorly sorted silty sands. Where observed, these lenses were frequently associated with isolated coarse woody debris (roots, root balls, and trunks) and tended to have erosional bases. The F2 facies averages 2.02 ±1.78 wt% TOC.

3.5.1.1.4 Lacustrine Basin

Deposits in the distal basin (closest to the dam) in former Lake Mills were relatively homogeneous, consisting predominantly of the F4 facies (Table 1). Field observations of the F4 facies define it as mud, which appears to be relatively clay-dominated at the base and to coarsen upward to become silt-dominated. These observations are confirmed by Gilbert and Link (1995), who found that 100% of sediments in the former Lake Mills basin were <0.075 mm. The F4 facies typically has few visible organics; where present, organic deposits occur as irregularly spaced, mm-scale lamina. These lamina are recognizably organic in color only, consisting of poorly preserved, amorphous organic detritus. In addition to organic lamina, organics in the basin of former Lake Mills occasionally include isolated fine and coarse woody debris. Visible lamina appear to increase in frequency closer to the delta and to contain larger fragments of identifiable leaves and needles. Despite the relative paucity of visible organics in former Lake Mills, samples of the F4 facies average 1.03 ±0.13 wt% TOC.

3.5.1.2 Lake Aldwell

Compared to the simple, Gilbert-style depositional model of Lake Mills, former Lake Aldwell was considerably more complex (Figure 3b). For the first decade and a half of Lake Aldwell's impoundment, abundant sediment supply and a relatively shallow upper basin appear to have caused the rapid progradation of a Gilbert-style delta into the upper reservoir. However, with the impoundment of Lake Mills upstream, the bedload supply to former Lake Aldwell was essentially cut off. As a result, delta progradation slowed and shifted in character. Deposited as an overprint on the distinct topset, foreset, and bottomset facies, the low-sediment Aldwell delta was characterized by a stable, extensively vegetated delta plain comprised of interbedded sand, gravel, and silty facies and an extensive delta top with a low-angle delta slope formed by the progradation of sandy mouth bars. Toeset facies and prodelta sands were essentially absent, with the prodelta considerably finer-grained than former Lake Mills.

3.5.1.2.1 Delta plain

Quantification of carbon storage in the upper environments of former Lake Aldwell lacks adequate data. The prominence of organic-rich facies like O3 and F5 in the delta top and delta slope suggests that carbon concentration is high in these depositional zones. One sample of Facies O4, a secondary deposit analogous to, but finer-grained than Facies O3, is 12.77 wt% TOC. Similarly, the F5 facies, with its fine-grained proximity to inflowing organic material and its leaf beds, probably has relatively high TOC, but analogous systems report widely varying carbon content. Floodplain sediments from 'partly confined younger forest' and 'unconfined old-growth multi-thread' headwater streams in Colorado have been reported to contain as much as 12% TOC (Wohl et al., 2012); however, samples from frequently inundated, low-lying floodplains in Quebec report average TOC of 1.74 ± 0.17 wt% (Saint-Laurent et al., 2016) and overbank sediments in rivers from the United Kingdom range from 2.17 to 5.07% (Walling et al., 2006). In contrast, samples from Facies G4, G8, and G9 in former Lake Aldwell average between 0.17 and 0.25 wt% TOC. Gravel-dominated areas of former Lake Aldwell thus appear to be extremely low in carbon.

3.5.1.2.2 Delta slope and delta top

The active delta top and delta slope in former Lake Aldwell were more complex than in former Lake Mills. The delta slope prograded as subaerial mouth bars, grading from fine-grained gravels (G7) to finer-grained HS2 and S3 deposits with depth in the reservoir. As in former Lake Mills, the S3 facies showed significant accumulation of organic detritus. In former Lake Aldwell, organic accumulation frequently included fragmented leaves and general litter, as well as the needles characteristic of former Lake Mills. No analytical samples from mouth bar deposits in former Lake Aldwell were collected; however, estimates from the S3 facies of former Lake Mills (Table 2) provide a reasonable estimate and suggest that significant carbon is stored in the mouth bar deposits of former Lake Aldwell.

The delta top in former Lake Aldwell was characterized by deposits associated with both proximal active-channel mouth bar and quiescent interdistributary areas. Proximal mouth bar deposits were characterized by fine channel lag gravels interbedded with well-sorted sands capped by thin-bedded leaves, needles, and general litter (G8, S2). Channel scour into in the more distal delta mouth bar deposits were frequently infilled with Facies O3, which appears to have been deposited as lag (Spicer, 1989). Inactive portions of the delta top were characterized by heterogeneous sand facies with variable, coarse-grained coarse woody debris (HS1, S1). In addition, the F5 facies, which consists of varve-like wave-rippled silt beds interbedded with horizons of mostly- intact leaves several centimeters thick, was prominent in former Lake Aldwell. This facies was not observed in former Lake Mills.

3.5.1.2.3 Prodelta and lacustrine basin

Downstream of the delta slope, the prodelta in former Lake Aldwell differed from former Lake Mills. While much of the former Lake Mills prodelta was dominated by the F1 facies, the F1 facies was essentially absent in former Lake Aldwell. Instead, the prodelta was dominated by the F2 facies. The mean wt% TOC in the F2 facies of former Lake Aldwell is 1.83 ±0.34. In contrast to the F4 facies, this is not significantly different from the mean wt% TOC in F2 deposits in former Lake Mills.

As in former Lake Mills, the lakebed deposits in former Lake Aldwell consisted of the F4 facies. However, in contrast to former Lake Mills, where the lakebed facies were deposited in a single elongate basin, the basin area of former Lake Aldwell consisted of two sub-basins separated by a submerged canyon known colloquially as “the gooseneck” (Figure 2A). The lower sub-basin of former Lake Aldwell was the site of extensive deposition during the dam removal drawdown, with several meters of accumulated sediment in areas. We group these sediments as F7 (fine-grained) and S4 (coarse-grained) and note that they tend to be fairly rich in carbon (Table 1). However, because they do not represent operating conditions during the life of the reservoir, we do not consider them in detail. F4 facies deposited in each sub-basin of former Lake Aldwell show no statistically significant difference in wt% TOC or C:N ratio and no longitudinal trend along the length of the reservoir ($R^2 = 0.0009$). However, both the mean wt% TOC and the mean C:N ratio of the F4 facies in former Lake Aldwell are significantly higher than in former Lake Mills ($p < 0.01$).

3.5.2 Organic matter provenance

Where is detrital carbon in reservoir sediments coming from? The stratigraphic prominence of detrital organics and correlation between visually organic-rich facies and higher concentrations of TOC, as discussed above, suggest that the former Lake Mills and Aldwell reservoirs were sinks for refractory pools of terrestrially-derived carbon. While a detailed investigation would require a multi-proxy approach utilizing biomarkers, isotopic analysis, and other methods, we can address this hypothesis at a broad scale by examining the ratio of carbon to nitrogen in samples collected from reservoir sediments by Wing (2014).

C:N ratios have long been utilized to infer trends in the source of sediment organic matter, predicated on the premise that terrestrial plant matter has a significantly higher C:N ratio than aquatic plants and phytoplankton (c.f. Tyson, 1995; Gordon & Goñi, 2003). In general, the C:N ratio of fresh terrestrial plant material is typically between 20 and 200, although woody detritus in headwater streams may have C:N ratios as high as 250 to 1340 (Tyson, 1995). On Vancouver Island, located directly north of the Elwha River watershed across the Strait of Juan de Fuca, Nuwer and Keil (2005) reported that fresh alder, maple, and fern leaves and hemlock needles to have C:N ratios between 36 and 46. After degradative processing, Tyson (1995) reports typical C:N ratios in terrestrial detritus as between 12 and 40, while recent sediments tend to range from the ones to teens. C:N ratios of >10-12 in estuarine or marine sediments are typically interpreted as indicative of terrestrial organic matter (Tyson, 1995; Hyne, 1978), while at the low end of the spectrum, phytoplankton and other aquatic plants tend to have C:N ratios between 6 and 8 (Redfield et al., 1963; Gordon and Goñi, 2003).

The C:N ratios in former Lake Mills vary from 5 to 32, with a mean of 12 ± 1, while former Lake Aldwell varies from 3 to 22, with a mean of 13±1 (Table 2). These values suggest that organic matter in both reservoirs is primarily derived from terrestrial input as opposed to autochthonous production. Spatial variation in C:N ratios, however, reveal intra-reservoir trends in allochthonous input. Assuming C:N ratio of ~19 measured in the S3 facies in former Lake Mills is applicable to former Lake Aldwell, the C:N ratio in the lower reservoir, as grouped according to characteristic facies, appears to decrease with distance from the river input. The F2 facies in former Lake Aldwell has a C:N ratio of 16 while the F4 facies has a C:N ratio of 13. We interpret this trend as evidence of the settling out of allochthonous material with distance from the delta. Former Lake Mills shows a similar trend, with the exception of the F1 facies (Figure 4b). Mean C:N ratios in the F1, F2, and F4 facies are all significantly different at the 95% level or better.

The strong relationship and positive slope between TOC and C:N in basin sediments of both reservoirs and the former Lake Mills prodelta sediments(Figure 5a) further suggests that higher TOC concentrations in these depositional zones are primarily the result of terrestrially-derived carbon influx, as opposed to primary production. Similarly, the positive slope of the regression suggests that variations in TOC are the result of real changes in organic matter supply to basin and prodelta sediments, as opposed to ‘concentration’ (or dilution) of the TOC signal with variation in sediment supply (which would tend to maintain a constant C:N ratio across a range of TOC concentrations). Although conclusive differentiation from soil carbon is not possible without additional proxies, the high overall C:N ratios suggest that this terrestrial influx is due to vascular plant debris, as opposed to soil matter. However, non-zero intercepts in the relationship between wt% TOC and total nitrogen (Figure 5b) also suggest the presence of inorganic nitrogen (probably ammonia, NH_4), which implies in-reservoir degradation products or a soil carbon influence.

However, former Lake Aldwell appears to have a more complicated relationship between wt% TOC and organic matter sources. Total nitrogen increases with wt% TOC more steeply in former Lake Aldwell than former Lake Mills, suggesting that higher TOC preservation may be the result of higher primary production (Figure 5b). The relationship between wt%TOC and C:N (Figure 5a) in former Lake Aldwell is more poorly defined than in the former Lake Aldwell basin or in former Lake Mills (R^2 = 0.30); relatively uniform, relatively high C:N ratios appear to contradict the relationship between wt% TOC and total N but probably actually reflect selective processing of proteins in phytoplankton during early diagenesis, increasing the C:N ratio (Tyson, 1990).

3.5.3 Carbon accumulation by depositional zone: toward quantification of carbon storage

The depositional zones mapped in Figure 2 are characterized by a set of typical facies, as discussed in Section 4.1, above (Figure 3). Here, we average the analytical results of samples collected from each depositional zone and apply them to the sediment volume of that area as calculated from as calculated from pre-removal and pre-dam DEMs (Bountry et al., 2011) to derive a zone-based estimate of total carbon accumulation in each reservoir (Table 3). Carbon content of facies without adequate sampling are estimated from literature.

Carbon storage in both former Lakes Aldwell and Mills appears to be concentrated in the delta slope/foreset depositional areas of the reservoirs, while the coarse-grained delta plain accounts for little storage (Table 3). While estimated foreset beds (including within the delta plain) in former Lake Mills represent only 14% of sediment deposition in the former reservoir, they account for ~30% of carbon storage (in contrast, lakebed deposits in former Lake Mills represent approximately 17% of total sediment volume but account for only 8% of carbon storage). This relationship also holds in former Lake Aldwell; however, former Lakes Aldwell and Mills show different patterns of carbon storage in their lakebed and prodelta zones. While the prodelta sediments in both reservoirs are proportionally richer in TOC than the lakebed sediments, in former Lake Aldwell, the lakebed sediments are estimated as 1.41 wt% TOC and store an estimated 22% of the total carbon in the reservoir, while the prodelta sediments are estimated as 1.84 wt% carbon but store only 9% total carbon accumulation. In contrast, the prodelta sediments in former Lake Mills are similar in carbon content (1.76 wt%), but, due to the volume of prodelta sediment accumulation, store approximately 23% of the total carbon in the reservoir while the lakebed sediments store approximately 8%. As estimated, the coarse-grained delta plain accounts for disproportionately little carbon storage relative to its accumulation rate; these values, however, are almost certainly underestimates, as they do not account for fine-grained deposition in the heterogeneous facies discussed above.

Based on the depositional zone-weighted calculations discussed above, we estimate that approximately 91 Gg of carbon was stored in former Lake Aldwell prior to its removal, with TOC accumulation rates per depositional zone ranging from 263 to 2414 $gCm^{-2}yr^{-1}$ (Table 3). Former Lake Mills is estimated to have stored approximately 330 Gg of carbon, with TOC accumulation rates per depositional zone ranging from 229 to 9,262 $gCm^{-2}yr^{-1}$. Given the necessary assumptions for this estimate, a numerical estimate of error is difficult to determine. However, we discuss potential sources of error, as well as the merits of this approach, below.

3.6 Discussion

Most previous studies of carbon burial in lake and reservoir sediments have assumed that storage is concentrated in relatively homogeneous, fine-grained portions of the reservoir and excluded deltaic regions (explicitly or implicitly) from sampling coverage (e.g., Mendonça et al., 2014; Sobek et al., 2009). This approach is based on the well-established negative correlation between grain size and TOC (Tyson, 1995; Hedges & Keil, 1995), and the assumption that sand and gravel units are essentially devoid of carbon, as “larger [organic] material (>100 um) may be conspicuous…[but] its contribution to the transported load is generally insignificant” (Tyson, 1995). However, our characterization of carbon storage in former Lakes Mills and Aldwell shows that, while fine-grained sediment deposited as the result of suspended sediment fallout is important to carbon burial in the reservoirs, it is moderate in comparison to storage in the complex, coarse sediment-dominated deltaic and delta-adjacent portions. (Figure 3; Table 3).

The deposition of coarse organic matter appears to be associated with event sedimentation, leading to complex patterns of organic matter burial, in both deltaic and prodelta regions, that vary between reservoirs. Gilbert and Link (1995) show that grain size in former Lake Mills progressively decreased downstream of the delta, with toeset/bottomset (proximal prodelta) sediments comprised of as little as 33% undifferentiated silt and clay, while samples designated ‘prodelta’ consisted of 88% undifferentiated clay and silt and 100% of basin sediments were composed of silt and clay. The typical negative correlation between grain size and average TOC would thus predict that TOC increase downstream in former Lake Mills. However, the prodelta sands (characterized by the S3 facies) average 2.19±3.16 wt% TOC, while the F1 facies (characteristic of the proximal prodelta) averages 1.26±0.23 wt% TOC, significantly less than the F2 facies (2.02 ±0.52; $p = 0.011$) characteristic of the distal prodelta, and the F2 facies is and the F4 facies is significantly greater than the average wt% TOC of the F4 facies characteristic of the lacustrine basin (1.03±0.14; $p = 0.0027$) (see stratigraphic column in Figure 3).We interpret this pattern to represent the importance of turbidity currents and deltaic slope failure, probably triggered by high-flow events. In former Lake Mills, deltaic processes appear to concentrate coarse organic matter in the toeset facies, while turbidity currents moving downslope carry organic matter beyond the proximal prodelta, which is characterized by interbedded fine-sand-and-silt F1 facies, to be deposited with the finer-grained F2 facies deposited as the distal runout of turbidity currents. However, the F1 facies is absent in former Lake Aldwell, probably as the result of less influence from turbidity currents associated with steep delta slope failure, as appears common in former Lake Mills. This interpretation is supported by the C:N relationships shown in Figures 4B and 5, which suggest a strong terrestrial signal which decreases with distance from the delta.

While few studies have assessed coarse organic matter in reservoirs, the limited evidence suggests that former Lakes Aldwell and Mills are not unique in their accumulations of coarse organic matter. In a study of six Gilbert-style tributary deltas exposed during a severe drought at Trinity (Clair Engle) Lake on the Trinity River in California (USA), Spicer and Wolfe (1987) described continuous beds of organic material composed of “large pieces of twigs and cones” and other plant material in the toeset beds and along the contours of sandy foreset beds. Additionally, a coring-based study at Englebright Lake, a multi-use, medium-sized reservoir on the Yuba River in northern California (USA), reported sandy deposits of “wood and leaf matter” in foreset/toeset deposits of the Gilbert-style deltas (Snyder et al. 2006; Pondell & Canuel, 2017); this study, one of few to sample from coarse-grained reservoir environments (Stratton et al., in prep), calculated an annual burial rate of 6600 g C/m^2/yr (as compared to the commonly-cited global estimate of ~400 g C/m^2/yr; Cole et al., 2007). Further, evidence suggests thick accumulations of organic material are not limited to depositional environments associated only with small, low-order streams. For example, a study of TOC distribution in two large reservoirs in Texas found that higher carbon concentrations were associated with deltaic areas than the distal, lacustrine portions of the reservoirs (Hynes, 1978). In contrast, Spicer (1989) found significant plant matter accumulation in the delta of a small (0.013 km^2), ca. 1815 reservoir in England, while Gastaldo et al. (1987) reported bedded leaf-litter horizons as much as 3 cm thick in delta mouth bar sands and active crevasse channels (morphologically similar to former Lake Aldwell) in the Mississippi River delta offshore of Mobile Alabama and interpreted them as the result of event deposition, which, when saturated, serve to baffle against the transport of sand and encourage burial of organic beds.

The location of reservoirs like former Lakes Mills and Aldwell in forested mountainous regions on a small, sixth-order stream suggests that coarse particulate organic matter and woody debris are likely to comprise a significant portion of the riverine organic load. In a detailed study in the western Oregon Cascades (a climate similar to that of the Elwha watershed) Naiman and Sedell (1979) found that coarse organic matter (>1mm) represented a mean of 50.0% of the benthic organic matter load in Lookout Creek, a fifth-order stream, and 40.4% of the benthic organic matter load in the McKenzie River, a seventh-order stream. These numbers, which excluded large woody debris >10 cm in diameter, were shown to be highly seasonally-dependent, with coarse particulate organic matter present in concentrations up to 69.2% during the spring freshet. Similarly, Goñi et al. (2013) found that particulate organic matter export from two small, mountainous rivers in the Pacific Norwest was dominated by winter high-flow events. Large woody debris also appears to comprise a significant portion of export from mountainous watersheds. Seo et al. (2008) found that large woody debris averaged 15% of total particulate organic carbon export from 121 dammed watersheds in Japan, while Rathburn et al. (2017) found that a large log raft, similar to that removed from the head of former Lake Mills prior to drawdown, accounted for approximately 20% of the long-term carbon storage rate in a small reservoir on a fourth-order stream in the Colorado (USA) Front Range.

We believe our estimates of carbon burial to be the most methodologically robust yet completed for reservoirs globally, but they should be viewed with several caveats. First, Because Glines Canyon and Elwha dams were removed in stages, sediments remaining in the reservoir basins after dam removal were heavily biased toward basin and prodelta facies. As a result, the basin and prodelta facies of former Lakes Aldwell and Mills are well represented in the analytical sampling results and we have a high degree of confidence in estimates from these regions. However, the more heterogeneous upper facies are poorly represented in the available data and rely on literature estimates from similar systems. Our estimates of deposition in heterogeneous regions are thus subject to a great deal of uncertainty; however, we believe our literature-based carbon concentrations to represent relatively conservative values.

Additionally, quantification of carbon in these coarse-grained sediments represents a significant challenge. Because transport and deposition of coarse-grained material (both sediment and detrital organic material) is typically event-based (e.g., Ambers, 2001; Snyder et al., 2006), organic delivery is seasonally controlled (Naiman and Sedell, 1979), and organic material is both 1) irregularly shaped and 2) variably dense depending on its relative saturation (Gastaldo, 1989), the transport and accumulation of coarse-grained organic matter in sediments is uniquely difficult to predict. Additionally, the scale of coarse organic matter, combined with the scale of heterogeneity in the facies architecture of reservoir sediments, makes the determination of a representative sediment volume problematic, and, once collected, most analytical methods are not equipped to measure coarse-grained material. Additionally, coring-based studies are unlikely to collect the full scale of woody debris stored in reservoir sediments due to of its irregular shape and relatively large diameter relative to the core barrel.

Previous efforts to determine predictive factors of carbon burial rates in reservoir sediments have relied on characteristics such as impoundment size, average temperature, catchment runoff, watershed cultivation, operations, longitude, or average slope. These efforts have had limited success, however, with results showing contradictory or weak explanatory relationships (c.f. Ritchie, 1989; Downing et al., 2008; Clow et al., 2015; Mendonça et al, 2017). The work in former Lakes Mills and Aldwell suggests that, while external factors such as watershed setting are indeed critical to understanding the supply of organic matter, carbon storage and spatial distribution in reservoirs cannot be assessed without an understanding of the dominant depositional processes operating in that system. As discussed above, organic matter storage in former Lake Mills appears to be concentrated in the foreset beds and prodelta regions of the reservoir. Neglecting organic matter storage in these regions and estimating total carbon storage in former Lake Mills based only on fine-grained, lacustrine zone samples (average wt% TOC 0.98%), as is common in many reservoir studies, would result in a ~47% underestimate of total carbon storage in former Lake Mills. In contrast, while organic matter storage in former Lake Aldwell is also delta-associated, as compared to former Lake Mills, the deltaic volume (both relative and absolute) in former Lake Aldwell is much lower. As a result, a similar, lacustrine-based sampling scheme would differ from our depositional-zone based estimates by only about 5% (based on average wt% TOC of 1.41%). However, if that sampling location were to instead sample from the large prodelta region (average wt% TOC = 1.84%), the resulting carbon estimate would yield a 30% (33 Gg C) *overestimate* of total carbon storage.

3.7 Conclusions and Implications

The stratigraphy-based investigation of organic matter accumulation in former Lakes Mills and Aldwell undertaken here illustrates both the importance of deltaic sedimentation and the importance of coarse organic matter to carbon storage in artificial reservoirs and other lacustrine environments. In particular, studies of reservoirs dominated by Gilbert-style deltas which fail to account for the importance of the foreset beds and prodelta regions to the storage of coarse organic matter stand to underestimate total carbon burial by up to 50%. While probably an oversimplification (Stratton et al., in press), Gilbert-style sedimentation remains the accepted “typical” paradigm in deep lakes and artificial reservoirs (e.g., Morris and Fan, 1998). Given the importance of particulate organic matter and woody debris to carbon storage in former Lake Mills and its location damming a mountainous, forested watershed, we suggest that 1) coarse organic matter deposition is probably underappreciated across a wide range of lacustrine environments, 2), dams in mountainous environments may represent a greater disruption to the global carbon budget than previously appreciated, and 3) the underestimation of organic matter storage in the coarse sediments of reservoirs is probably significant at a global scale.

However, while carbon storage was concentrated in the delta and prodelta regions in both reservoirs, differences in the deltaic structure result in subtle differences in the volumetric distribution of organic matter between former Lakes Aldwell and Mills. While similar in terms of surface area and watershed characteristics, the application of a Gilbert-style paradigm to former Lake Aldwell would result in a significant mischaracterization of the controls on organic matter storage and the reservoir’s evolution through time; however, given our current understanding of reservoir sedimentation and organic matter processing dynamics, these differences are difficult to predict and suggest our current paradigm of organic matter storage in reservoirs and other lacustrine environments is incomplete.

Because organic matter stored in reservoirs constitutes a fraction of the sediment itself, it cannot be characterized in isolation from sedimentation processes and the exo- and endo-genic factors which influence them. Additionally, the added complexities of variable density (i.e., varying saturation), complex shapes, seasonal fluctuations in organic matter supply, and subsequent biogeochemical processing, further complicate the dynamics of organic matter sedimentation and long-term storage in reservoirs. However, by using stratigraphic characterization as a tool to understand the processes influencing sediment and organic matter transport and deposition, this work provides a framework to tease out the controls on carbon storage in reservoir sediments and other lacustrine environments, to better understand the fundamental role of rivers and lakes in the global carbon cycle, and to investigate the global impact of dam construction on global biogeochemical cycles.

3.8 Acknowledgements

This work could not have been completed without the extensive field and analytical data that Seth Wing generously provided; we thank him heartily. We also thank Miguel Goñi for providing a thoughtful review of the manuscript. Collection of unpublished data from Lake Billy Chinook (Jefferson County, Oregon) was supported by a grant to L. Stratton from the HydroResearch Foundation.

3.9 References Cited

Abraham, J., Allen, P.M., Dunbar, J.A., and Dworkin, S.I. (1999). Sediment type distribution in reservoirs: sediment source versus morphometry. *Environmental Geology*, 38, p. 101–110. https://doi.org/10.1007/s002540050406

Acker, S. A., Beechie, T. J., and Shafroth, P. B. (2008). Effects of a natural dam-break flood on geomorphology and vegetation on the Elwha River, Washington, USA. *Northwest Science*, 82(sp1), p. 210-223. https://doi.org/10.3955/0029-344X-82.S.I.210

Ambers, R.K. (2001). Using the sediment record in a western Oregon flood-control reservoir to assess the influence of storm history and logging on sediment yield. *Journal of Hydrology*, 244(3-4), p. 181–200. https://doi.org/10.1016/S0022-1694(01)00331-6

Bates, C.C. (1953). Rational theory of delta formation. *AAPG Bulletin*, 37(9), p. 2119-2162.

Batt, G.E., Brandon, M.T., Farley, K.A., and Roden-Tice, M. (2001). Tectonic synthesis of the Olympic Mountains segment of the Cascadia wedge, using two-dimensional thermal and kinematic modeling of thermochronological ages. *Journal of Geophysical Research*, *106*, B11/ https://doi.org/0.1029/2001JB000288

Bountry, J., Ferrari, R., Wille, K., and Randle, T.J. (2011). 2010 Survey Report for Lake Mills and Lake Aldwell on the Elwha River, Washington: United States Department of the Interior Bureau of Reclamation Technical Report SRH-2010-23, 66 p.

Brandon, M.T., Roden-Tice, M.K., and Garver, J.I. (1998). Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, northwest Washington State. *GSA Bulletin*, 110(8), 985–1009. https://doi.org/10.1130/0016-7606(1998)110<0985:LCEOTC>2.3.CO;2

Carnero-Bravo, V., Merino-Ibarra, M., Ruiz-Fernandez, A. C., Sanchez-Cabeza, J. A., and Ghaleb, B. (2015). Sedimentary record of water column trophic conditions and sediment carbon fluxes in a tropical water reservoir (Valle de Bravo, Mexico). *Environmental Science and Pollution Research*, *22(6)*, 4680-4694. https://doi.org/10.1007/s11356-014-3703-0

Childers, D., Kresch, D.L., Gustafson, S.A., Randle, T.J., Melena, J.T., and Cluer, B. (2000). Hydrologic data collected during the 1994 Lake Mills drawdown experiment, Elwha River, Washington. United States Geological Survey Report 99–4215, 115 p.

Clow, D. W., Stackpoole, S. M., Verdin, K. L., Butman, D. E., Zhu, Z. L., Krabbenhoft, D. P., and Striegl, R. G. (2015). Organic Carbon Burial in Lakes and Reservoirs of the Conterminous United States. *Environmental Science & Technology*, 49(24), 14741-14741. https://doi.org/ 10.1021/acs.est.5b00373

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Middelburg, J. J., and Melack, J. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems,* 171-184. https://doi.org/10.1007/s10021-006-9013-8

Dean, W.E., and Gorharm, E. (1998). Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. *Geology*, 26(6), 535-538.

Deemer, B. R., Harrison, J. A., Li, S. Y., Beaulieu, J. J., Delsontro, T., Barros, N., Bezerra-Neto, J. F., Powers, S. M., dos Santos, M. A., and Vonk, J. A., 2016, Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis. *Bioscience*, 66(11). 949-964. https://doi.org/10.1093/biosci/biw117

Downing, J. A., J. J. Cole, J. J. Middelburg, R. G. Striegl, C. M. Duarte, P. Kortelainen, Y. T. Prairie, and K. A. Laube (2008). Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century. *Global Biogeochemical Cycles*, 22, GB1018, https://doi.org/10.1029/2006GB002854

Draut, A.E., Logan, J.B., and Mastin, M.C. (2011). Channel evolution on the dammed Elwha River, Washington, USA. *Geomorphology*, 127, 71–87. https://doi.org/10.1016/j.geomorph.2010.12.008

Duda, J.J., Freilich, J.E., and Schreiner, E.G. (2008). Baseline Studies in the Elwha River Ecosystem Prior to Dam Removal: Introduction to the Special Issue. *Northwest Science,* 82(sp1), 1–12. https://doi.org/10.3955/0029-344X-82.S.I.1

Federal Energy Regulatory Commission (1991). Draft environmental impact statement: Elwha and Glines Project, FERC no. 2683 and 588. Washington, D.C., Federal Energy Regulatory Commission, 250 p.

Gastaldo, R.A. (1989). Preliminary observations of phytotaphonomic assemblages in a subtropical/temperate Holocene bayhead delta: Mobile Delta, Gulf Coast plain, Alabama: *Review of Palaeobotany and Palynology,* 58(1), 61-83. https://doi.org/10.1016/0034-6667(89)90057-2

Gastaldo, R.A. (1994). The genesis and sedimentation of phytoclasts with examples from coastal environments In A. Traverse (Ed.), *Sedimentation of Organic Particles* (pp. 103-128). New York: Cambridge University Press.

Gastaldo, R., Douglass, D., & McCarroll, S. (1987). Origin, Characteristics, and Provenance of Plant Macrodetritus in a Holocene Crevasse Splay, Mobile Delta, Alabama. *PALAIOS,*2(3*),* 229-240. doi:10.2307/3514673

Gilbert, G.K. (1885). The topographic features of lake shores, in Fifth Annual report of the United States Geological Survey 1883-84,. 69-123.

Gilbert, J., and Link, R.A. (1995). Alluvium distribution in Lake Mills, Glines Canyon Project and Lake Aldwell, Elwha Project, Washington: U.S. Department of the Interior, Elwha Technical Series PN-95-4, 60 p.

Gleick, P.H. (2000). Water futures: A review of global water resources projections. In F.R. Rijsberman (Ed.), *World Water Scenarios* (pp. 27-45). London: Earthscan.

Gordon, E. S., and Goni, M. A. (2003). Sources and distribution of terrigenous organic matter delivered by the Atchafalaya River to sediments in the northern Gulf of Mexico. *Geochimica Et Cosmochimica Acta,* 67(3), 2359-2375. https://doi.org/10.1016/S0016-7037(02)01412-6

Hedges, J. I., and Keil, R. G. (1995). Sedimentary organic-matter preservation - an assessment and speculative synthesis.: *Marine Chemistry,* 49(2-3), 81-115. https://doi.org/10.1016/0304-4203(95)00008-F

Hyne, N.J. (1978). The distribution and source of organic matter in reservoir sediments: *Environmental Geology*, 2(5), 279-287. https://doi.org/10.1007/BF02430674

Huc, A.Y. (Ed.). (1990). *Deposition of Organic Facies,* AAPG Studies in Geology, 30. Tulsa, Oklahoma: American Association of Petroleum Geologists.

Jacinthe, P. A., Filippelli, G. M., Tedesco, L. P., and Raftis, R. (2012). Carbon storage and greenhouse gases emission from a fluvial reservoir in an agricultural landscape. *Catena,* 94, 53-63. https://doi.org/10.1016/j.catena.2011.03.012

Keith, M.K., Wallick, J.R., Taylor, G., Mangano, J., White, J. and Schenk, L. (2016). Geomorphic responses of gravel bed rivers to fine sediment releases during annual reservoir drawdowns: Spatial patterns and magnitude of aggradation along Fall Creek and Middle Fork Willamette River, Oregon. Abstract EP53C-0984 presented at 2016 Fall Meeting, AGU, San Francisco, California, 12-16 December.

Kostic, S., Parker, G., and Marr, J.G. (2002). Role of turbidity currents in setting the foreset slope of clinoforms prograding into standing fresh water. *Journal of Sedimentary Research*, 72, 353–362.

Kunz, M. J., Wuest, A., Wehrli, B., Landert, J., and Senn, D. B. (2011). Impact of a large tropical reservoir on riverine transport of sediment, carbon, and nutrients to downstream wetlands. *Water Resources Research*, 47(12), W12531, https://doi.org/10.1029/2011WR010996..

McNulty, T. (2009). Olympic National Park: A natural history (second edition), Seattle: University of Washington Press, 384 pp.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N. and Wisser, D. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, 9,: 494–502. https://doi.org/10.1890/100125

Maavara, T., Lauerwald, R., Regnier, P. and Van Capellen, P. (2017). Global perturbation of organic carbon cycling by river damming. *Nature Communications*, 8, https://doi.org/0.1038/ncomms15347

Mendonça, R, Müller, R.A., Clow, D., Verpoorter, C., Raymond, P., Tranvik, L.J., and Sobek, S. (2017). Organic carbon burial in global lakes and reservoirs. *Nature Communications*, 8(1694), https://doi.org/10.1038/s41467-017-01789-6 | www.nature.com/naturecommunications

Mendonça, R., Kosten, S., Sobek, S., Cardoso, S. J., Figueiredo-Barros, M. P., Estrada, C. H. D., and Roland, F. (2016). Organic carbon burial efficiency in a subtropical hydroelectric reservoir: *Biogeosciences*, 13(11), 3331-3342. https://doi.org/10.5194/bg-13-3331-2016

Mendonça, R., Kosten, S., Sobek, S., Cole, J. J., Bastos, A. C., Albuquerque, A. L., Cardoso, S. J., and Roland, F. (2014). Carbon Sequestration in a Large

Hydroelectric Reservoir: An Integrative Seismic Approach. *Ecosystems*, 17(3), 430-441. https://doi.org/10.1007/s10021-013-9735-3

Mendonça R, Kosten S, Sobek S, Barros N, Cole JJ, Tranvik L, Roland F. (2012). Hydroelectric carbon sequestration. *Nature Geoscience*, 5(12*)*, 838–40. https://doi.org/10.1038/ngeo1653

Morris, G. L., and Fan, J. (1998), Reservoir Sedimentation Handbook, New York, New York: McGraw-Hill, 898 pp.

Mulholland, P.J. and Elwood, J.W. (1982). The role of lake and reservoir sediments as sinks in the perturbed global carbon cycle. *Tellus*, 34(5), 490-499, https://doi.org/10.1111/j.2153-3490.1982.tb01837.x

Naiman, R.J. and Sedell, J.R. (1979). Benthic organic matter as a function of stream order in Oregon. *Archive für Hydrobiologie*, 97,404e422.

Nilsson, C. Reidy, C.A., Dynesius, M. and Revenga, C. (2005). Fragmentation and flow regulation of the world's large river systems. *Science,* (305), 405-408. https://doi.org/10.1126/science.1107887

National Park Service (1996). Final Environmental Impact Statement (EIS): Elwha River Ecosystem Restoration Implementation. Port Angeles, WA. National Park Service, U.S. Department of the Interior, Available: http:// www.nps.gov/olym/naturescience/loader.cfm?csModule=security/ getfile&PageID=136253 [accessed 17 October 2017].

Nuwer, J.M., and Keil, R.G. (2005). Sedimentary organic matter geochemistry of Clayoquot Sound, Vancouver Island, British Columbia. *Limnology and Oceanography*, 50(4), 1119-1128, https://doi.org/10.4319/lo.2005.50.4.1119.

Pess, G.R., McHenry, M.L., Beechie, T.J., and Davies, J. (2008). Biological Impacts of the Elwha River Dams and Potential Salmonid Responses to Dam Removal. *Northwest Science*, 82(sp1), 72–90, https://doi.org/10.3955/0029-344X-82.S.I.72.

Pittman, B., Jones, J. R., Millspaugh, J. J., Kremer, R. J., and Downing, J. A. (2013). Sediment organic carbon distribution in 4 small northern Missouri impoundments: implications for sampling and carbon sequestration. *Inland Waters,* 3(1), 39-46. https://doi.org/10.5268/IW-3.1.507

Pondell, C.R. and Canuel, E.A. (2017). The role of hydrodynamic sorting on the accumulation and distribution of organic carbon in an impoundment: Englebright

Lake, California, USA: *Biogeochemistry*, 133(2), 129-145. https://doi.org/10.1007/s10533-017-0319-8

Rathburn, S.L., Bennett, G.L., Wohl, E.E., Briles, C., McElroy, B. and Sutfin, N. (2017). The fate of sediment, wood, and organic carbon eroded during an extreme flood, Colorado Front Range, USA. *Geology*, 45(6), 499-502.

Randle, T.J., Bountry, J.A., Ritchie, A., and Wille, K. (2015). Large-scale dam removal on the Elwha River, Washington, USA: Erosion of reservoir sediment. *Geomorphology*, 246, 709–728, https://doi.org/10.1016/j.geomorph.2014.12.045.

Redfield, A. C., Ketchum, B.H., and Richards, F.A. (1963). The influence of organisms on the composition of seawater, in Hill, M.N. (Ed.), The Sea, 2. *Interscience*, 26–77.

Renwick, W. H., Smith, S.V., Bartley, J.D., and Buddemeir, R.D. (2005).The role of impoundments in the sediment budget of the conterminous United States. *Geomorphology*, 71, 99–111. https://doi.org/10.1016/j.geomorph.2004.01.010

Ritchie, J C. and McHenry, J.R. (1977). The Distribution of Cs-137 in Some Watersheds in the Eastern United States. *Health Physics, 32*, 101-105.

Ritchie, J. C., 1989, Carbon content of sediments of small reservoirs. *Journal of the American Water Resources Association*, 25(2), 301-308. https://doi.org/10.1111/j.1752-1688.1989.tb03065.x.

Ritchie, J. C., Gill, A. C. and McHenry, J. R. (1975). A comparison of nitrogen, phosphorus, and carbon in sediments and soils of cultivated and non-cultivated watersheds in the North Central States. *Journal of Environmental Quality*, 4, 339-341.

Saint-Laurent, D., Paradis, R., Drouin, A., and Gervais-Beaulac, V. (2016). Impacts of Floods on Organic Carbon Concentrations in Alluvial Soils along Hydrological Gradients Using a Digital Elevation Model (DEM). *Water*, 8(5). https://doi.org/10.3390/w8050208

Schuster, J. E. (2005). Geological Map of Washington State GM-53. Washington State Department of Natural Resources, Olympia.

Seo, J. I., Nakamura, F., Nakano, D., Ichiyanagi, H. and Chun, K. W. (2008). Factors controlling the fluvial export of large woody debris, and its contribution to organic carbon budgets at watershed scales. *Water Resources Research*, 44, W04428, https://doi.org/ 10.1029/2007WR006453

Shotbolt, L.A., Thomas, A.D., and Hutchinson, S.M. (2005). The use of reservoir sediments as environmental archives of catchment inputs and atmospheric pollution. *Progress in Physical Geography,* 29(3), 337-361. https://doi.org/10.1191/0309133305pp452ra

Snyder, N. P., Wright, S. A., Alpers, C. N., Flint, L. E., Holmes, C. W., and Rubin, D. M. (2006). Reconstructing depositional processes and history from reservoir stratigraphy: Englebright Lake, Yuba River, northern California. *Journal of Geophysical Research-Earth Surface,* 111(F4). https://doi.org/0.1029/2005JF000451

Sobek, S., DelSontro, T., Wongfun, N., and Wehrli, B. (2012). Extreme organic carbon burial fuels intense methane bubbling in a temperate reservoir. *Geophysical Research Letters,* 39 (L01401*),* https://doi.org/10.1029/2011GL050144

Spicer, R.A. (1989). The formation and interpretation of plant fossil assemblages, *in* Callow, J.A.(Ed.), *Advances in Botanical Research,* 16, 96-150. San Diego, California: Academic Press, Inc.

Spicer, R.A., and Wolfe, J.A. (1987). Plant taphonomy of late Holocene deposits in Trinity (Clair Engle) Lake, northern California. *Paleobiology*, 13(2), 227–245.

Stallard, R.F., (1998). Terrestrial sedimentation and the carbon cycle: coupling weathering and erosion to carbon burial. *Global Biogeochemical Cycles*, 12(2), 231-257. https://doi.org/10.1029/98GB00741

Stratton, L.E. and Grant, G.E. (in press). Autopsy of a reservoir: facies architecture in a multi-dam system, Elwha River, Washington, USA, *GSA Bulletin.*

Syvitski, J.P., Vörösmarty, C.J., Kettner, A.J., and Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science,* 308(5720), 376-380. https://doi.org/10.1126/science.1109454

Tabor, R. W. (1987). Geology of Olympic National Park. Northwest Interpretive Association, Seattle, WA.

Tabor, R.W. and Cady, W.M. (1978). The structure of the Olympic Mountains, Washington; analysis of a subduction zone. United States Geological Survey Professional Paper 1033, 38 p.

Thonton, K.W., Kimmel, B.L., and Payne, F.E. (1990). Reservoir Limnology: ecological perspectives. Somerset, New Jersey: John Wiley & Sons, Inc.

Trask, P.D. (1939). Organic content of recent marine sediments, in Trask, P.D. (Ed.), Recent Marine Sediments. Tulsa, Oklahoma: American Association of Petroleum Geologists, p. 428-453.

Twichell, D.C., Cross, V.A., Hanson, A.D., Buck, B.B., Zybala, J.G., and Rudin, M.J. (2005) Seismic architecture and lithofacies of turbidites in Lake Mead (Arizona and Nevada, U.S.A.), an analog for topographically complex basins. *Journal of Sedimentary Research,* 75(1), 134-148.

Tyson, R.V. (1995). Sedimentary organic matter: organic facies and palynofacies: New York, Chapman & Hall, 615 p.

Vanni, M. J., Renwick, W. H., Bowling, A. M., Horgan, M. J., and Christian, A. D. (2011). Nutrient stoichiometry of linked catchment-lake systems along a gradient of land use. *Freshwater Biology*, 56(5), 791-811. https://doi.org/10.1111/j.1365-2427.2010.02436.x

Viseras, C., Fernández, J., García-García, F., Soria, J.M., Calvache, M.L., and Jáuregui, P. (2009). Dynamics of sedimentary environments in the accelerated siltation of a reservoir: the case of Alhama de Granada, southern Spain. *Environmental Geology*, 56(7),1353–1369. http://dx.doi. org/10.1007/s00254-008-1231-2.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P. and Syvitski, J.P.M. (2003). Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change,* 39, 169-190. https://doi.org/10.1016/S0921-8181(03)00023-7

Walling, D.E., Fang, D., Nicholas, A.P., and Sweet, R.J. (2006). River flood plains as carbon sinks, in Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006.

Waters, C.N., Zalasiewicz, J., Summerhayes, C., Barnosky, A.D., Poirier, C., Galuszka, A., Cearreta, A., Edgeworth, M., Ellis, E.C., Ellis, M., Jeandel, C., Leinfelder, R., McNeill, J.R., Richter, D.D., Steffen, W., Syvitski, J., Vidas, D., Wagreich, M., Williams, M., Zhisheng, A. Grinevald, J., Odada, R., Oreskes, N., and Wolfe, A.P. (2016). The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science*, 351(6269), *137*. http://dx.doi. org/10.1126/ science.aad2622

Wetzel, R. G. (2001). Limnology: Lake and River Ecosystems, 3rd ed., London: Academic Press, Elsevier, 1006 p.

Wildman, R.A., Pratson, L.F., DeLeon, M., and Hering, J.G. (2011). Physical, Chemical, and Mineralogical Characteristics of a Reservoir Sediment Delta (Lake Powell, USA) and Implications for Water Quality during Low Water Level. *Journal of Environment Quality*, 40(2), 575-586. https://doi.org/10.2134/jeq2010.0323

Wing, S., 2014, Reservoir sediment carbon along the Elwha River after dam removal: University of Washington, https://dlib.lib.washington.edu/researchworks/handle/1773/26432 (accessed August 2016).

Wohl, E., Dwire, K., Sutfin, N., Polvi, L., and Bazan, R. (2012). Mechanisms of carbon storage in mountainous headwater rivers: *Nature Communications*, 3(1253). https://doi.org/10.1038/ncomms2274

Wright, L.D. (1977). Sediment transport and deposition at river mouths: a synthesis: *Geological Society of America Bulletin*, 88(6), 857–868. https://doi.org/10.1130/0016-7606(1977)88<857:STADAR>2.0.CO;2

3.10 Figures

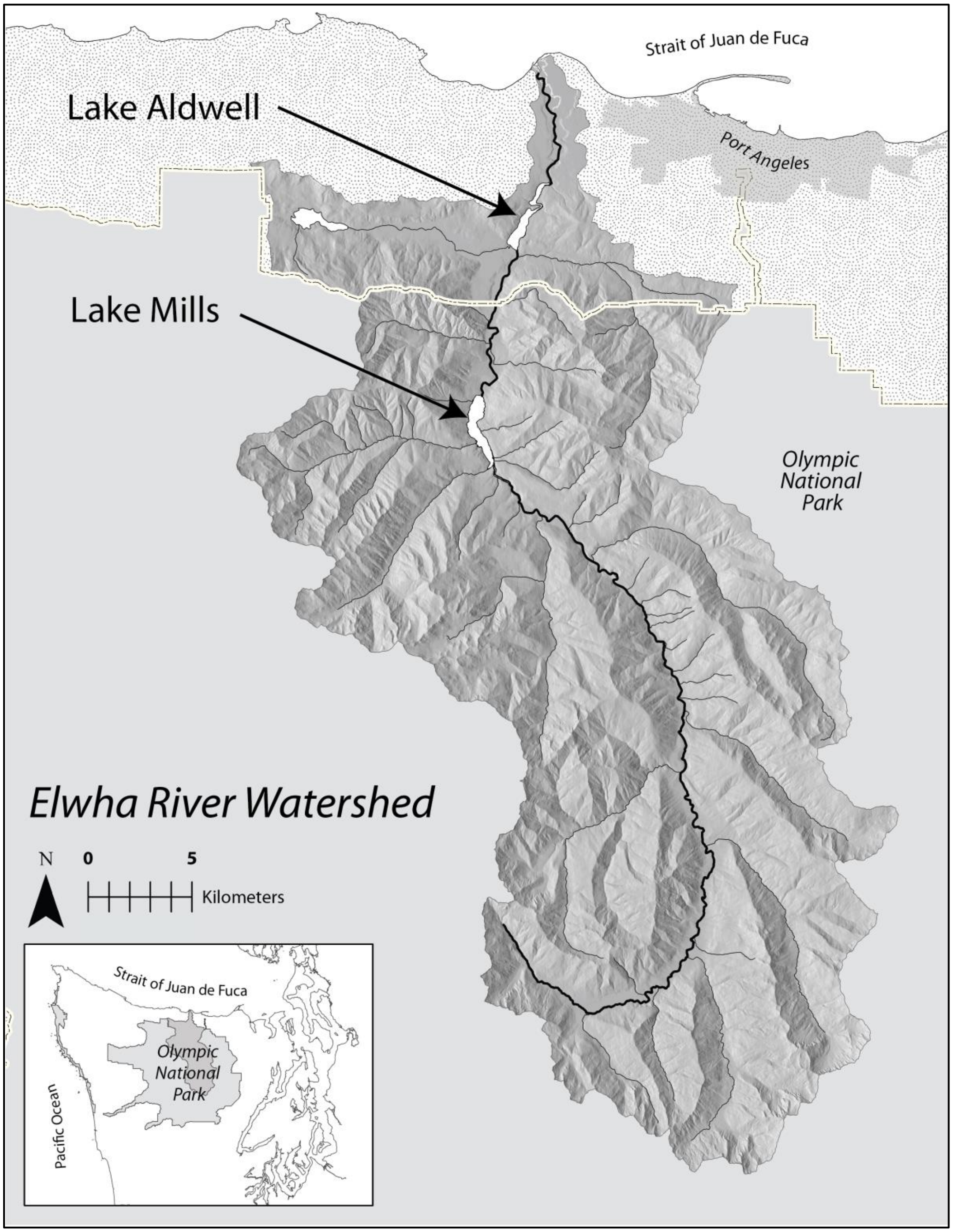


Figure 3-1. Location of former Lakes Aldwell and Mills in the Elwha River watershed, Clallam County, Washington

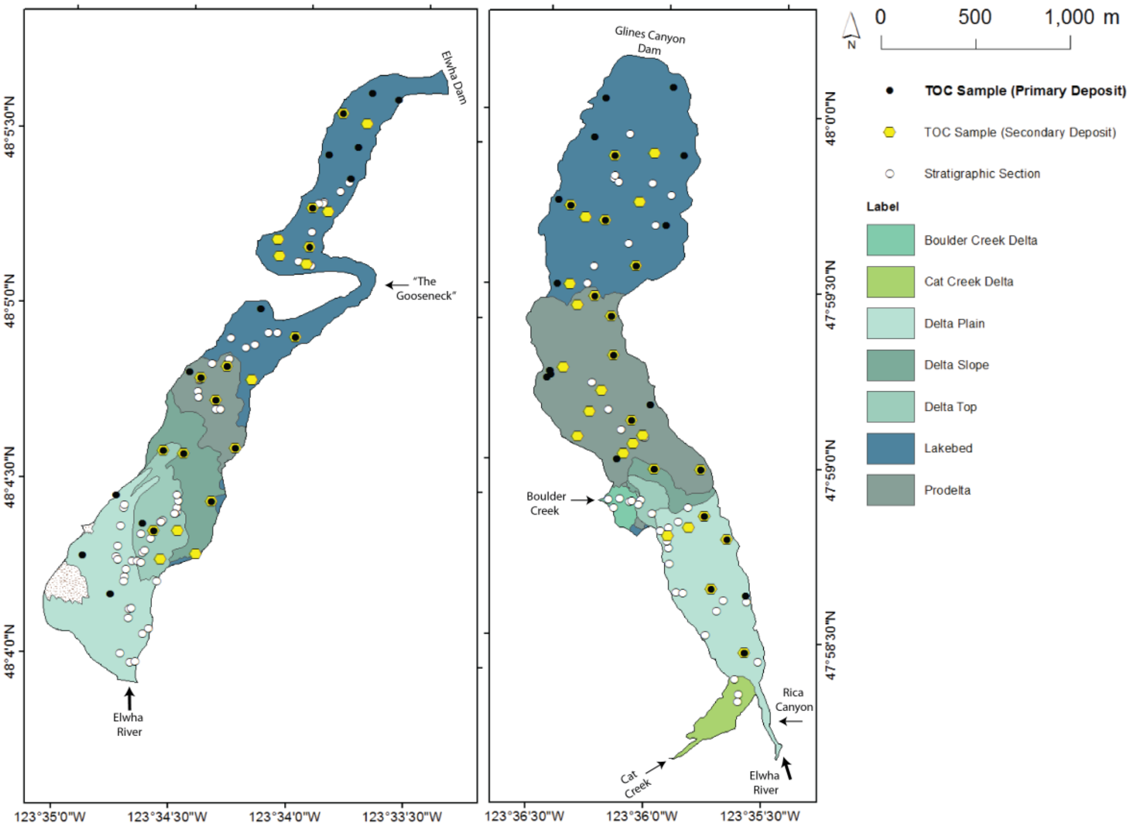


Figure 3-2. Depositional zones and sampling locations. Depositional zones are based on stratigraphic facies architecture and sediment thickness, as delineated in Stratton et al. (submitted). "Primary deposit" refers to sediments deposited during normal operations of the reservoir while "secondary deposit" refers to sediments emplaced during the dam removal process. Stratigraphic sections are described in more detail in Stratton et al. (submitted). TOC samples are described in more detail in Wing (2014).

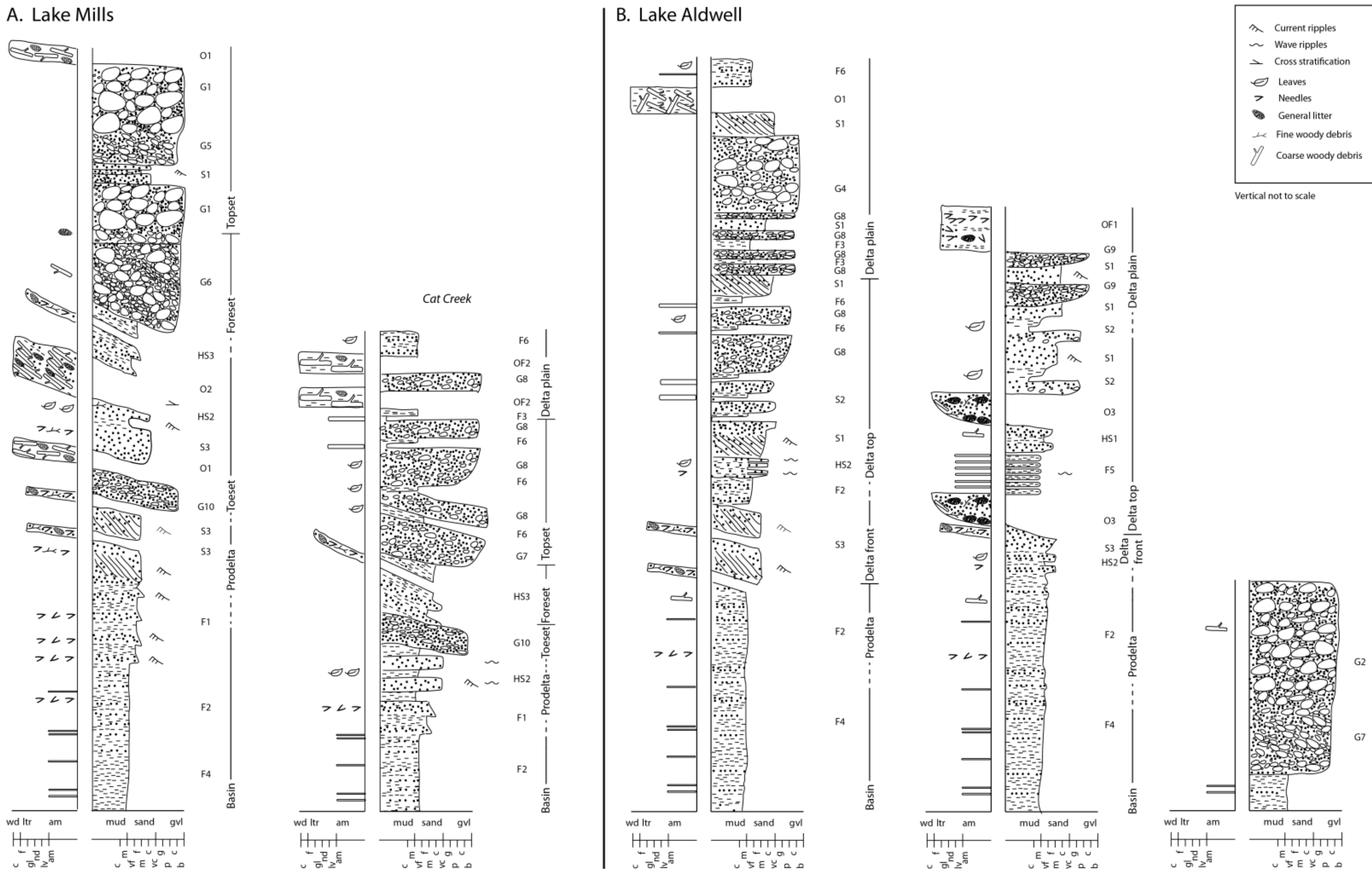


Figure 3-3 Composite stratigraphic columns, former Lakes Mills (A) and Aldwell (B). Left axis represents organic matter-dominated units; right axis represents mineral-dominated sediments. Organic matter classification codes are explained in supplementary data. Facies codes are explained in Table 1. Cat Creek is a minor tributary near the head of the reservoir (Figure 2) and represents the only complete section preserved in reservoir sediments by the summer of 2014. Multiple columns in (B) reflect lateral variability deltaic progradation in former Lake Aldwell.

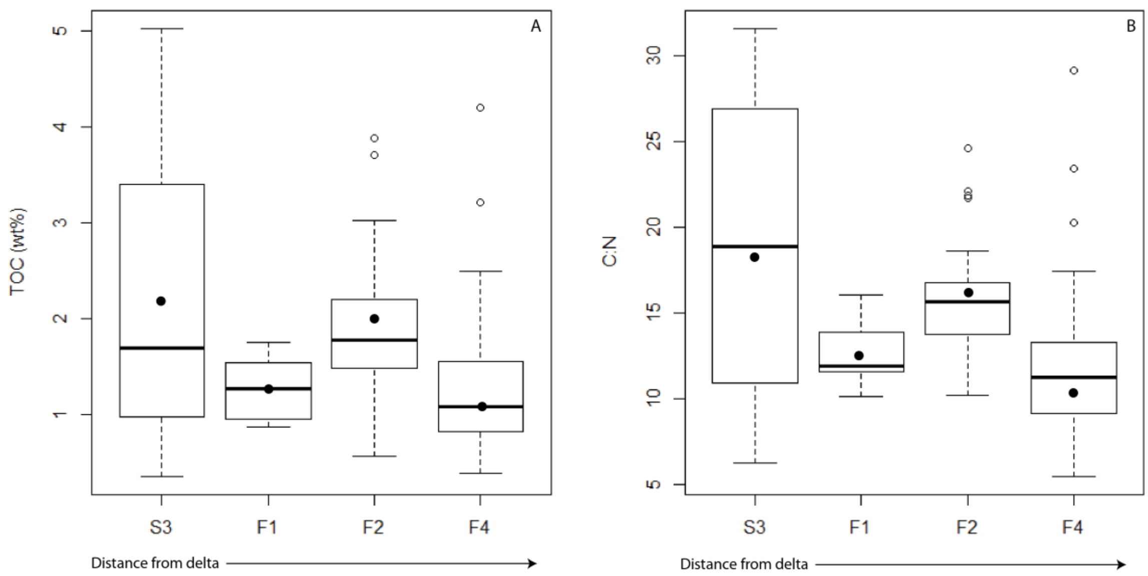


Figure 3-4. Whisker plot of prodelta and basin facies wt% TOC (A) and C:N ratio (B) in former Lake Mills. Black dots represent mean values; white dots represent outliers.

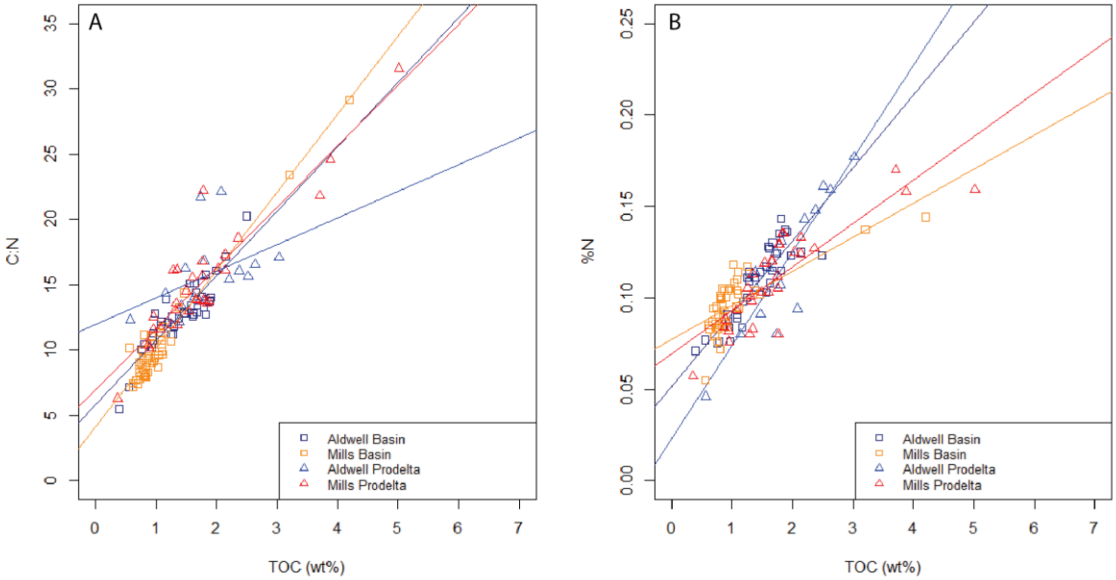


Figure 3-5. A) Relationship between TOC and C:N by depositional zone. Former Lake Mills basin r^2 = 0.9413, prodelta r^2 = 0.839; former Lake Aldwell basin r^2 = 0.7827, prodelta r^2 = 0.2953. B) Relationship between TOC and N by depositional zone. Note non-zero intercepts.

3.11 Tables

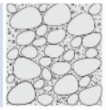
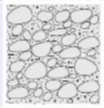
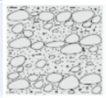
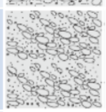
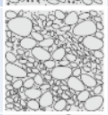
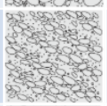
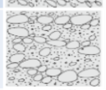
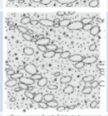
Facies		Description	Bedding	Visible Organic Detritus
G1		Unchannelized cobble-boulder gravels; massive to crudely stratified. Clast- to matrix-supported; matrix sandy to pebbly. Little silt.	Sheet-like, laterally extensive beds to 5 m thickness	Isolated, intact to well preserved fine (average diameter ~2 -5 cm and coarse (tree with intact root balls) woody debris. <5% surface exposure.
G2		Unchannelized, poorly sorted large pebble to cobble gravels; similar to G1 but finer-grained and consistently matrix-supported; some silt in matrix.	Sheet-like, laterally extensive beds to 2 m thickness	Isolated, intact to well preserved fine (average diameter ~2 -5 cm and coarse (tree with intact root balls) woody debris. <5% surface exposure.
G3		Matrix-supported, very poorly sorted angular gravels; inverse grading and elevated clasts common.	Subhorizontal to 20° dip, maximum 0.5 m, local unit pinches out downstream	None observed
G4		Weakly graded, weakly channelized silty sandy gravel with lag. Lag shows imbrication, occasional weak channel form.	As multi-story ~0.5 m bed; laterally extensive, pinches out over hundreds of meters	Isolated, intact to well preserved fine (average diameter ~2 -5 cm and coarse (tree with intact root balls) woody debris. <5% surface exposure.
G5		Cross-stratified, well-imbricated pebble to cobble gravels. Open framework to clast-supported.	Steeply-dipping cross beds 20-30 cm thick; laterally extensive.	Isolated, intact to well preserved fine (average diameter ~2 -5 cm) woody debris. <5% surface exposure.
G6		Interbedded pebble, small cobble, and coarse sand to granule conglomerate. Individual beds moderately to well sorted; may be open framework	Steeply dipping (25-30°) beds to 0.5 m thickness, uniform geometry	Intact to well preserved fine woody debris and general litter interbedded as lenses within conglomerate and granule beds. <5% surface exposure.
G7		Crudely stratified, gently dipping pebble to cobble gravels. Matrix- to clast-supported; little silt.	Forms sigmoidal foreset on scale of 2-3 m; individual beds ~10 cm	Isolated, intact to well preserved fine (average diameter ~2 -5 cm and coarse (tree with intact root balls) woody debris. <5% surface exposure.
G8		Weakly channelized, well-sorted sandy gravel with prominent lag; little silt. Clast-supported, weakly imbricated to massive. Finer and less silty than G4.	Subhorizontal to broadly undulating; beds 10 cm to 0.5 m thick	Frequently interbedded with organic units but absent to very rare in G8.
G9		Tabular to channelized pebble gravels and pebbly sand. Clast-supported, rarely open-framework. Little to no silt.	Complexly bedded; sheet-like tabular beds cut by channel forms with migration lag	Frequently interbedded with organic units but absent to rare in G9.
G10		Low-angle, tabular pebbly gravel beds interbedded with sigmoidally cross-bedded coarse and very coarse sands. Individual beds to ~1 m thick but pinch out.	Gently dipping to broadly undulatory, laterally extensive but variable.	Absent to very rare.

Table 3-1. Facies designations, former Lakes Aldwell and Mills. Facies are coded by dominant grain size (G = gravel; S = sand; HS = heterogeneous (sandy); F = fines (a field-scale determination including silt and clay); O = organic; OF = organics in fine-grained units or with a fine-grained matrix). Numeric values indicate fining of dominant grainsize within group based on field description (e.g., facies G1 is generally coarser-grained than facies G8 but both are dominated by gravel).

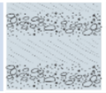
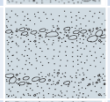
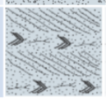
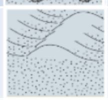
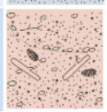
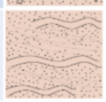
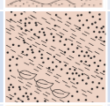
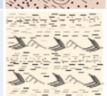
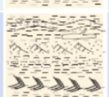
Facies		Description	Bedding	Visible Organic Detritus
S1		Well-sorted medium to coarse sand with granules forming well-developed cross beds and planar-laminated beds.	Multiple cosets of sheet-like units, pinch out downstream. Maximum thickness ~0.5 m.	Trace; as <1 mm thick lamina
S2		Medium to coarse or very coarse sand and fine pebbles; moderately to well sorted with little internal structure. No silt.	Laterally extensive, gently dipping; beds typically 10-20 cm.	Well-bedded, intact to well-preserved needles, leaves, and general litter; organic beds to 4 cm thick or as clasts in sand to 10 cm thick.
S3		Well-sorted medium to fine sand with interbedded organics. Planar to sigmoidal cross-lamina, climbing ripples common. Beds typically ~ 10 to 50 cm.	Subhorizontal to undulating; extensive, relatively uniform.	Intact to well-preserved needles, general litter, and fine woody debris individually cross stratified with sand or as beds to 4-10 cm thick separating ripple cosets. Where occur as beds, clast-supported to open framework. ~15% surface exposure.
S4		Very thick beds of massive to cross-laminated sand and silty sand with climbing ripples and load structures; gravel absent.	Beds to several meters thick; upper contact frequently channelized	Intact to well-preserved leaves, needles with subordinate general litter and rare fine woody debris. Interlaminated with climbing ripples and cross-lamina; Absent to ~15% surface exposure.
HS1		Variable, chaotic to channelized or weakly bedded, poorly sorted sand with medium to coarse organics and rare pebbles.	Sheet-like. Extensive, bottom contact erosive. Grades finer laterally, typically little fabric.	Intact to well-preserved general litter, fine and rare coarse woody debris; chaotically interbedded with sand units. Variable; to 15% surface exposure.
HS2		Fine to medium cross-laminated sand regularly interbedded with wave rippled or wavy-bedded muds to ~5 cm thick. Silt subordinate to sand beds.	Subhorizontal to gently dipping; silt interbeds pinch out but laterally extensive	Intact needles and leaves (less common) in lee of cross-lamina and ripples; also as imbricated, densely packed leaf beds in lenses to 5 cm thick. Intact fine woody debris occasionally imbricated in sandy beds. <10% total surface exposure.
HS3		Well-sorted, interbedded sand and pebbles separated by thin silt beds. Beds laminated with pebbles imbricated along dip.	Steeply dipping (25-30°) beds to 0.5 m thickness, uniform geometry	Intact needles and leaves (less common) in lee of cross-lamina and ripples; also as imbricated, densely packed leaf beds in lenses to 5 cm thick. Intact fine woody debris occasionally imbricated in sandy beds. <10% total surface exposure.
F1		Striped mud and sand lamina and beds, frequently with needles. Sand beds to 5 cm, cross-laminated, increase up-section relative to silt beds.	Subhorizontal; laterally extensive. Thickness from 0.5 m to many meters	Intact to well-preserved general litter and needles as lamina or lenses to 1 cm thick; also individually in lee of ripples. ~10% of total surface exposure.
F2		Interlaminated mud and silty sand with organics. Parallel to weakly wavy, rare ripple formsets or climbing ripples.	Subhorizontal, laterally extensive. Thick bedded (to several meters).	Irregular, 1 mm to 1 cm lamina of well- to poorly-preserved general litter; also well-preserved needles in lee of rare ripples, well-preserved general litter in lee of isolated coarse woody debris and whole trees.
F3		Laminated to massive very fine mud beds, typically blue-gray. Maximum bed thickness 10 cm, often representing single current ripple formset.	Subhorizontal, laterally continuous. Interbedded with organics, gravels.	Absent to trace (well-preserved needles)

Table 3-1 (continued). Facies designations, former Lakes Aldwell and Mills. Facies are coded by dominant grain size (G = gravel; S = sand; HS = heterogeneous (sandy); F = fines (a field-scale determination including silt and clay); O = organic; OF = organics in fine-grained units or with a fine-grained matrix). Numeric values indicate fining of dominant grainsize within group based on field description (e.g., facies G1 is generally coarser-grained than facies G8 but both are dominated by gravel)

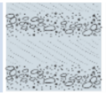
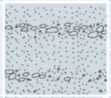
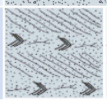
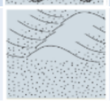
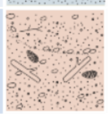
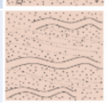
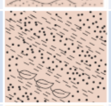
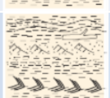
Facies		Description	Bedding	Visible Organic Detritus
S1		Well-sorted medium to coarse sand with granules forming well-developed cross beds and planar-laminated beds.	Multiple cosets of sheet-like units, pinch out downstream. Maximum thickness ~0.5 m.	Trace; as <1 mm thick lamina
S2		Medium to coarse or very coarse sand and fine pebbles; moderately to well sorted with little internal structure. No silt.	Laterally extensive, gently dipping; beds typically 10-20 cm.	Well-bedded, intact to well-preserved needles, leaves, and general litter; organic beds to 4 cm thick or as clasts in sand to 10 cm thick.
S3		Well-sorted medium to fine sand with interbedded organics. Planar to sigmoidal cross-lamina, climbing ripples common. Beds typically ~ 10 to 50 cm.	Subhorizontal to undulating; extensive, relatively uniform.	Intact to well-preserved needles, general litter, and fine woody debris individually cross stratified with sand or as beds to 4-10 cm thick separating ripple cosets. Where occur as beds, clast-supported to open framework. ~15% surface exposure.
S4		Very thick beds of massive to cross-laminated sand and silty sand with climbing ripples and load structures; gravel absent.	Beds to several meters thick; upper contact frequently channelized	Intact to well-preserved leaves, needles with subordinate general litter and rare fine woody debris. Interlaminated with climbing ripples and cross-lamina; Absent to ~15% surface exposure.
HS1		Variable, chaotic to channelized or weakly bedded, poorly sorted sand with medium to coarse organics and rare pebbles.	Sheet-like. Extensive, bottom contact erosive. Grades finer laterally, typically little fabric.	Intact to well-preserved general litter, fine and rare coarse woody debris; chaotically interbedded with sand units. Variable; to 15% surface exposure.
HS2		Fine to medium cross-laminated sand regularly interbedded with wave rippled or wavy-bedded muds to ~5 cm thick. Silt subordinate to sand beds.	Subhorizontal to gently dipping; silt interbeds pinch out but laterally extensive	Intact needles and leaves (less common) in lee of cross-lamina and ripples; also as imbricated, densely packed leaf beds in lenses to 5 cm thick. Intact fine woody debris occasionally imbricated in sandy beds. <10% total surface exposure.
HS3		Well-sorted, interbedded sand and pebbles separated by thin silt beds. Beds laminated with pebbles imbricated along dip.	Steeply dipping (25-30°) beds to 0.5 m thickness, uniform geometry	Intact needles and leaves (less common) in lee of cross-lamina and ripples; also as imbricated, densely packed leaf beds in lenses to 5 cm thick. Intact fine woody debris occasionally imbricated in sandy beds. <10% total surface exposure.
F1		Striped mud and sand lamina and beds, frequently with needles. Sand beds to 5 cm, cross-laminated, increase up-section relative to silt beds.	Subhorizontal; laterally extensive. Thickness from 0.5 m to many meters	Intact to well-preserved general litter and needles as lamina or lenses to 1 cm thick; also individually in lee of ripples. ~10% of total surface exposure.
F2		Interlaminated mud and silty sand with organics. Parallel to weakly wavy, rare ripple formsets or climbing ripples.	Subhorizontal, laterally extensive. Thick bedded (to several meters).	Irregular, 1 mm to 1 cm lamina of well- to poorly-preserved general litter; also well-preserved needles in lee of rare ripples, well-preserved general litter in lee of isolated coarse woody debris and whole trees.
F3		Laminated to massive very fine mud beds, typically blue-gray. Maximum bed thickness 10 cm, often representing single current ripple formset.	Subhorizontal, laterally continuous. Interbedded with organics, gravels.	Absent to trace (well-preserved needles)

Table 3-1 (continued). Facies designations, former Lakes Aldwell and Mills. Facies are coded by dominant grain size (G = gravel; S = sand; HS = heterogeneous (sandy); F = fines (a field-scale determination including silt and clay); O = organic; OF = organics in fine-grained units or with a fine-grained matrix). Numeric values indicate fining of dominant grainsize within group based on field description (e.g., facies G1 is generally coarser-grained than facies G8 but both are dominated by gravel)

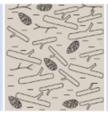
Facies		Description	Bedding	Visible Organic Detritus
OF2		Coarse organics (branches to 10 cm diameter, sticks, root balls) in mud matrix. Tightly packed, clast-supported	Irregular; often in lee of stranded root ball	Organic unit; variable from well-preserved leaves to fine woody debris. General litter most common; forms beds to 20 cm thick (>90% surface exposure).

Table 3-1 (continued). Facies designations, former Lakes Aldwell and Mills. Facies are coded by dominant grain size (G = gravel; S = sand; HS = heterogeneous (sandy); F = fines (a field-scale determination including silt and clay); O = organic; OF = organics in fine-grained units or with a fine-grained matrix). Numeric values indicate fining of dominant grainsize within group based on field description (e.g., facies G1 is generally coarser-grained than facies G8 but both are dominated by gravel)

	TOC (wt%)				C:N				
Facies	avg	min	max	CI-95	avg	min	max	CI-95	n
G1	0.34	0.24	1.04	0.08	5.67	4.22	13.17	0.93	19
G4*	0.17	0.16	0.19	0.04	5.67	5.33	6.33	1.43	3
G8	0.25	0.23	0.26	0.18	7.15	6.34	7.97	10.25	2
G9*	0.17	0.13	0.20	0.03	4.33	3.25	5.00	0.70	6
S2	1.23	0.74	1.97	0.40	13.41	8.39	17	3.21	7
S3	2.19	0.36	5.02	3.16	18.9	6.28	31.55	16.97	4
S4†	1.3	0.24	4.47	0.29	13.49	4.93	29.22	1.77	45
O4	12.77	-	-	-	40.54	-	-	-	1
F1	1.26	0.87	1.76	0.23	12.61	10.15	16.07	1.45	10
MF2	2.02	0.95	3.88	0.52	16.33	12.54	24.56	2.13	13
AF2	1.83	0.57	3.03	0.34	15.45	10.21	22.11	1.69	16
F2	1.91	0.57	3.88	0.28	15.84	10.21	24.56	1.26	29
MF4	1.03	0.56	3.2	0.14	10.39	7.19	23.4	0.87	48
AF4	1.41	0.39	2.49	0.15	12.88	5.48	20.24	0.84	37
F4	1.2	0.39	3.21	0.1	11.47	5.48	23.4	0.66	85
F7†	2.2	0.83	6.24	0.67	16.98	9.87	25.04	2.53	17

**Samples run after long-term storage using [look up Miguel's machine]*
†Facies interpreted to be secondary only (i.e., deposited as part of dam removal drawdown)

Table 3-2 . Analytical carbon content data by facies. "M" prefix indicates samples from former Lake Mills; "A" prefix indicates samples from former Lake Aldwell; all others not distinguished by lake. CI-95 indicates 95% confidence interval. Facies included in Table 1 but not listed here are either minor components of overall deposition or were not sampled for inclusion in analytical data.

Depositional Zone	Volume (m^3)	Volume (%)	Total Mass (g)†	Avg TOC (weight %)	TOC (Gg)	% Carbon Stored	TOC Accumulation Rate (g C/m^2/yr)
Lake Aldwell*	4.57E+06		6.73E+12		90.7		742
Lakebed	1.34E+06	28%	1.47E+12	1.41%	20.7	23%	415
Prodelta	3.87E+05	8%	4.26E+11	1.84%	7.8	9%	577
Delta slope	5.86E+05	12%	9.97E+11	2.19%**	21.8	24%	1,402
Delta top	8.63E+05	18%	1.47E+12	2.19%**	32.1	35%	2,414
Delta plain	1.40E+06	29%	2.37E+12	0.35%***	8.3	9%	263
Lake Mills§	1.51E+07		2.03E+13		320		*2,098*
Lakebed	2.51E+06	17%	2.77E+12	0.98%	27.1	8%	*416*
Prodelta	3.82E+06	25%	4.20E+12	1.76%	73.9	23%	*1,636*
Boulder Creek bottomset	*9.07E+04*	1%	9.97E+10	1.76%	1.76	1%	746
Delta plain bottomset	*2.17E+06*	*14%*	2.39E+12	1.76%	42.0	13%	*1,474*
Delta slope	7.08E+05	5%	1.20E+12	2.64%	31.8	10%	*9,262*
Delta top	6.80E+05	4%	1.16E+12	2.19%	25.3	8%	*8,880*
Delta plain foreset	*2.17E+06*	*14%*	3.69E+12	2.64%‡	97.4	30%	*3,417*
Boulder Creek foreset	*9.07E+04*	1%	1.54E+11	2.64%‡	4.1	1%	1,729
Delta plain topset	*2.17E+06*	*14%*	3.69E+12	0.35%***	12.9	4%	*453*
Boulder Creek topset	*9.07E+04*	1%	1.54E+11	0.35%***	0.5	0%	229
Cat Creek	6.02E+05	4%	8.43E+11	0.35%***	3.0	1%	590

*Lake Aldwell excludes landslide volume in delta plain
**Estimated from Facies S3, this study
***Estimated from Facies G1, this study.
†Calculated using dry bulk density from Wing et al. 2014
‡Pondell and Canuel 2017
§Calculated by dividing thickness of Boulder Creek wedge and mainstem delta plain into thirds representing topset, foreset, and bottomset beds, after Stratton et al. (submitted) and Gilbert and Link (1995)

Table 3-3. Depositional volumes and estimated area-weighted carbon accumulation rates. Average TOC as estimated from samples collected from depositional zones; where sampling was inadequate, literature values applied (as indicated in table).

3.12 Supplementary Information

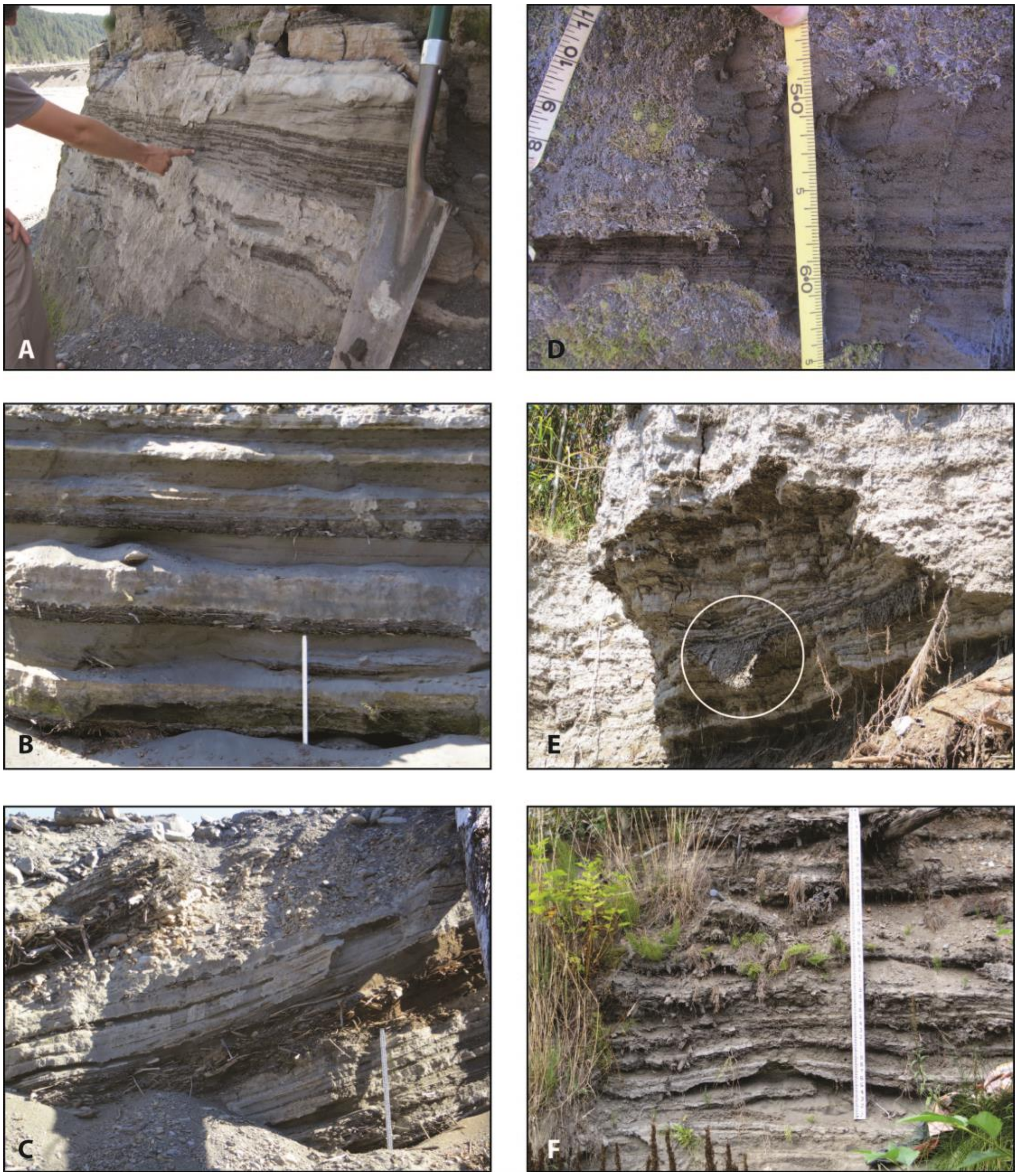


Figure SI-3-1. Examples of detrital organic-rich facies. Spade blade is 40 cm; imperial stadia rod is 4.7 ft (1.43 m) A) Conifer needle bedding in transitional bedding from F1 to S3 facies (former Lake Mills). B) fine woody debris interbedded with fine and medium sand in S3 (former Lake Mills). Silty-appearing beds are surface veneer. C) Foreset beds preserved near Boulder Creek delta, former Lake Mills. D) Finely-laminated organic matter in F2 facies, former Lake Aldwell E) F5 facies in former Lake Aldwell; circle is mat of bedded leaves. F) Interbedded coarse- and fine-grained facies in delta top of former Lake Aldwell

Type		
Category		**Description**
Amorphous		Organic matter too fine and/or degraded beyond identification; typically recognized based on color change in sediments
Litter	**Leaves**	Broadleaves; no systematic species identification attempted but most appear to be deciduous maple spp.
	Needles	Conifer needles; no species identification attempted.
	General litter	Cones, twigs to 1 cm diameter, bark fragments
Fine woody debris		Woody debris greater than 1 cm but less than 10 cm average diameter
Coarse woody debris		Woody debris > 10 cm diameter. Primarily branches and logs; includes root wads and full trunks

Degradation Status	
Category	**Description**
Intact	Little evidence of transport or degradation; outline and/or bark generally intact, little to no rounding
Well preserved	Fragmented but recognizable by type, bark absent on woody debris, clasts show rounding
Poorly preserved	Fragments degraded past recognition

Table-SI-3-1. Type and degradation criteria to classify organic matter in section exposures

Lake Aldwell* (as of 1994)		Grain size (% total accumulation)							Total volume (%)
Area		Clay, silt (<0.075) mm(yd³)	Sand (0.075 - 0.425 mm)	Sand (0.0425 - 5 mm)	Gravel (5 - 19 mm)	Gravel (19 - 75 mm)	Cobbles (75 - 125 mm)	Cobbles (125 - 300 mm)	
1	Lake Aldwell delta seds, upstream portion	0.01	0.02	0.02	0.02	0.01	0.01	0.00	**0.09**
2	Lake Aldwell delta seds, downstream portion	0.17	0.14	0.03	0.00	0.00	0.00	0.00	**0.35**
3	Indian Creek delta and similar sediments	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.01**
4	Margin sediments, Lake Aldwell delta	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.02**
5	Prodelta	0.29	0.05	0.00	0.00	0.00	0.00	0.00	**0.34**
6	reservoir floor, upper	0.06	0.01	0.00	0.00	0.00	0.00	0.00	**0.06**
7	reservoir floor, gooseneck	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
8	reservoir floor, downstream	0.13	0.01	0.00	0.00	0.00	0.00	0.00	**0.13**
9	reservoir rim	0.01	0.00	0.00	0.00	0.00	0.00	0.00	**0.01**
Sum		**0.67**	**0.22**	**0.06**	**0.02**	**0.02**	**0.01**	**0.00**	**1**

Lake Mills* (as of 1994)		Grain size (% total accumulation)							Total volume (%)
Area		**Clay, silt (<0.075) mm(yd³)**	**Sand (0.075 - 0.425 mm)**	**Sand (0.0425 - 5 mm)**	**Gravel (5 - 19 mm)**	**Gravel (19 - 75 mm)**	**Cobbles (75 - 125 mm)**	**Cobbles (125 - 300 mm)**	
1	Rica Canyon sediments (to elevation 600 feet)	0.00	0.00	0.01	0.01	0.01	0.00	0.00	**0.04**
2	Cat Creek Fan	0.00	0.00	0.01	0.01	0.02	0.00	0.00	**0.05**
3	Boulder Creek Fan *(largest estimated volume)	0.00	0.00	0.01	0.01	0.01	0.00	0.00	**0.03**
4	Prodelta sediments	0.22	0.03	0.00	0.00	0.00	0.00	0.00	**0.25**
5	Reservoir floor sediments	0.13	0.00	0.00	0.00	0.00	0.00	0.00	**0.14**
6T	*Topset sediments (upper unit)*	*0.00*	*0.00*	*0.00*	*0.00*	*0.01*	*0.00*	*0.00*	*0.02*
6F	*Foreset sediments (mid-unit)*	*0.00*	*0.01*	*0.01*	*0.00*	*0.00*	*0.00*	*0.00*	*0.02*
6B	*Bottomset sediments (lower unit)*	*0.01*	*0.01*	*0.01*	*0.00*	*0.00*	*0.00*	*0.00*	*0.03*
6	Lake Mills delta, upstream portion	0.01	0.02	0.03	0.01	0.01	0.00	0.00	**0.08**
7T	*Topset units (upper unit)*	*0.01*	*0.02*	*0.06*	*0.03*	*0.01*	*0.00*	*0.00*	*0.13*
7F	*Foreset units (mid-unit)*	*0.02*	*0.04*	*0.07*	*0.01*	*0.00*	*0.00*	*0.00*	*0.14*
7B	*Bottomset sediments (lower unit)*	*0.08*	*0.05*	*0.02*	*0.00*	*0.00*	*0.00*	*0.00*	*0.15*
7	Lake Mills delta, downstream portion	0.11	0.11	0.15	0.04	0.01	0.00	0.00	**0.43**
Sum		**0.48**	**0.17**	**0.20**	**0.07**	**0.06**	**0.01**	**0.01**	**1.00**

Table-SI-3-2. Reproduced data from Gilbert and Link (1995), recalculated as percent of total accumulation

4 A **stratigraphic framework to evaluate the deposition and burial of organic matter in reservoir sediments**

Laurel E. Stratton and Gordon E. Grant

for submission to Limnology and Oceanography: Letters

4.1 Abstract

Transporting water, sediment, and nutrients while acting as sites of intense biogeochemical transformation, rivers represent a critical nexus of geologic, hydrologic, ecologic, and atmospheric cycles. These cycles, however, have been profoundly impacted by the global boom in dam construction. Evidence shows that reservoirs are hotspots of biogeochemical activity as compared to natural systems, with intensified rates of nutrient cycling, including primary production, mineralization, and sedimentation (burial); however, global estimates of carbon sequestration rates in reservoir sediments vary by three orders of magnitude, while individual-reservoir estimates vary by four orders of magnitude and over only 37 reservoirs. By connecting form to process, stratigraphically-based conceptual models of four styles of reservoir sedimentation suggest that organic matter deposition varies systematically, evolves through time, and that coarse grained organic matter and woody debris contributes significantly to carbon burial in a variety of reservoirs, suggesting that current methods of evaluation underestimate total carbon burial globally.

4.2 Introduction

Transporting water, sediment, and nutrients while acting as sites of intense biogeochemical transformation, rivers represent a critical nexus of geologic, hydrologic, ecologic, and atmospheric cycles. These cycles, however, have been profoundly impacted by the global boom in dam construction, which now affects approximately 50% of large rivers, intercepts approximately 40% of global discharge, and has increased the Earth's terrestrial surface water area by ~7.3% (Vörösmarty et al., 2003, Syvitsky et al., 2005; Nilsson et al., 2005; Downing et al., 2006; Lehner et al., 2011).

Evidence shows that reservoirs are hotspots of biogeochemical activity as compared to natural systems, with intensified rates of nutrient cycling, including primary production, mineralization, and sedimentation (burial) (Cole et al., 2007; Maavara et al., 2017). High rates of terrestrial carbon input, as well as high aquatic productivity due to large nutrient inputs, appear to create environments that promote the mineralization and off-gassing of large volumes of greenhouse gases (St. Louis 2000; Abril 2005; Guérin et al. 2006; Tranvik et al., 2009; Jacinthe et al., 2012; Clow et al., 2015). The most recent synthesis of investigations into greenhouse gas emissions from reservoirs suggests that annual global emissions are 0.8 (0.5-1.2) Pg carbon dioxide (CO_2) equivalent per year, primarily due to methane (CH_4) (Deemer et al., 2016).

Reservoirs also appear to intensify the burial of carbon, however (Mendonça et al., 2017). Most CH_4 (and much CO_2) production occurs in the shallow sediments of aquatic environments, where heterotrophic microbes mineralize organic matter that is supplied as a fraction of the sediment supply or as rain-out from in-reservoir production (c.f. Wetzel, 2001; Burdige, 2007). As sediment builds up, any particulate organic matter that escapes mineralization is buried and typically considered to have been removed from the “active” pool of carbon cycling. The balance between mineralization and burial can be expressed as the *burial efficiency* (BE):

$$BE = \frac{QOC_{z*}}{QOC_{z_0}} = 1 - \frac{ROC_{z0-z*}}{QOC_{z_0}} \text{ (eqn 1)}$$

where *ROC* is the respiration of organic carbon in the sediments from depth the surface water interface (z_0) to burial (z_*) and the rate of carbon burial at depth is the difference between carbon input and respiration (c.f. Henrichs and Reeburg, 1987; Sobek et al. 2009, 2011; Blair and Aller, 2012):

$$QOC_{z*} = QOC_{z_0} - ROC_{z_0-z*} \text{ (eqn 2)}$$

While great strides have been made in recent years toward quantifying and characterizing the mineralization/respiration (ROC) portion of burial efficiency (c.f. Deemer et al., 2016; Drake et al., 2017), the dynamics of burial in reservoir sediments (QOC) remain relatively unexamined (c.f. Mendonça et al., 2012). As we discuss below, the relationship between carbon burial and sedimentation in reservoirs is poorly characterized, exposing gaps in our fundamental understanding of the transport, processing, and deposition of organic matter in fluvial and lacustrine systems, and creating uncertainty in estimates of the net impact of dams to the global carbon cycle.

4.3 Current estimates of carbon burial

4.3.1 Continental- to global-scale averages

The globally-averaged rate of reservoir carbon burial is most often cited as about 400 gC $m^{-2}yr^{-1}$ or 0.2 Pg Cyr^{-1}, figures given in several different studies but derived from a set of overlapping datasets (Table 1). In general, these studies combine literature-derived estimates of reservoir surface area, average sedimentation rate, and average bulk density with a “typical” sediment carbon content of 1 to 3 weight percent (wt%). However, area-weighted, average global reservoir carbon burial rate estimates vary by three orders of magnitude (Table 1). Ritchie (1989) found that the normalized burial rate in 58 reservoirs across the United States was higher than 400 gC $m^{-2}yr^{-1}$ but highly variable, (estimated as 675±739 gC $m^{-2}yr^{-1}$), while Downing and others (2008), using wt% carbon data collected from small reservoirs and farm ponds of Iowa (0.008 to 42.089 km^2; median = 0.37 km^2), calculated an average burial rate of 2,100 gC $m^{-2}yr^{-1}$, from which they extrapolated a global carbon burial rate as high as 1,000 gC $m^{-2}yr^{-1}$. More recently, however, regression-based studies of carbon content in reservoir sediments across the United States and globe have suggested area-normalized burial rates of between 144 and 363 gC $m^{-2}yr^{-1}$ (0.06 Pg C yr^{-1}; Clow et al., 2015; Mendonça et al., 2017), while a spatially-explicit mass balance modeling approach estimated burial rates of only 80 gC $m^{-2}yr^{-1}$ -- less than 25% that of older estimates (Maavara et al., 2017).

In addition to the large variance in attempts to quantify burial rates, attempts to determine predictive variables using these regional- and global-scale datasets have been inconclusive or contradictory. Downing and others (2008) and Mendonça and others (2017) both found that carbon burial was negatively correlated with impoundment size, while Mendonça and others (2017) also found relationships between carbon burial rates and temperature, catchment runoff, watershed cultivation, and average slope (n = 59). However, in their 58-reservoir dataset collected from across the United States, Ritchie (1989) found no significant difference in carbon accumulation by land use, reservoir operation, watershed size, reservoir size, or vegetation type. Ritchie (1989) did, however, report that reservoirs west of 90° longitude had significantly higher accumulation rates than those east of 90° longitude (p = 0.10), a finding supported by Clow and others

(2015) and a trait they attributed to higher sedimentation rates. As noted by Clow and others (2015), the multiple linear regression model from which they developed a global estimate of average carbon burial explained only 39% of variance, "indicating that a substantial amount of the variance in measured [organic carbon] concentrations remained unexplained."

A potential explanation for this large variance in estimates and predictive capability is the limited availability and range of data relative to the global reservoir population. As estimated by Lehner and others (2011), there are more than 16.7 million impoundments globally, ranging from farm ponds <$1.0x10^{-4}$ km^2 (0.01 ha) to reservoirs covering thousands of square kilometers. The widely-cited average global reservoir burial estimate of ~400 gC $m^{-2}yr^{-1}$ (Table 1), however, was derived from several investigations into carbon content in small reservoirs in the United States, the largest of which was comprised of data from 58 reservoirs across the United States (Ritchie, 1989). Earlier studies included a maximum of 12 impoundments which were geographically limited to the northeast and southern United States (Ritchie et al., 1975; Ritchie and McHenry, 1977). Similarly, the work of Downing and others (2008), while applied to 40 reservoirs across the Midwestern state of Iowa (USA) and widely cited as an argument for global burial rates of 1,000 gC $m^{-2}yr^{-1}$ or more, is derived from only 16 reservoir samples. The work of Mendonça and others (2016) is probably the most comprehensive analysis of carbon burial in reservoir sediments (exclusive of Clow et al., 2015, discussed further below). However, with data from 59 reservoirs across the world, this study still represents <0.1% of the $2.8x10^6$ reservoirs estimated to be >$1.0x10^{-3}$ km^2 (0.1 ha; Lehner et al., 2011).

Further, these continental- and global-scale studies appear to be 1) heavily biased toward smaller reservoirs, and 2) deficient in reliable data not derivable from global-scale GIS-based analysis. For example, while the data of Ritchie et al. (1989) has been extrapolated to support estimates of the total global average, only two of the reservoirs measured were larger than 0.5 km^2 (50 ha), the largest size class reported therein, while 37 (64%) were less than 0.1 km^2 (10 ha). Similarly, the median reservoir area tabulated by Mendonça and others (2016) was 0.30 km^2. However, 92% of global reservoir surface area (inclusive of regulated natural lakes) is accounted for by reservoirs larger than 1 km^2 (Lehner et al., 2011). Additionally, while many potentially important factors determining carbon burial, such as reservoir area, watershed area, land use, land cover, precipitation, and watershed terrain, can typically be determined using GIS-based analysis, the availability of reservoir-specific data such as dam height, age, trophic status, capacity, and critically, operational regime and pre-dam bathymetry, tends to be limited (Lehner et al., 2011; Mendonça et al., 2014). As a result, no global-scale efforts to determine explanatory variables on carbon burial have been able to evaluate these potentially critical factors.

4.3.2 Individual reservoir estimates

What insight, then, can be gleaned from studies of individual reservoirs? In a comprehensive search of the peer-reviewed, English-speaking literature, we identified only 37 reservoirs with carbon burial rates and total magnitudes calculated from direct measurements of carbon and sediment accumulation (see Supplementary Information). These data include, where possible, those reservoirs used in the calculation of the global average rates discussed above, but exclude data reported only in aggregate (e.g., Ritchie, 1989), based exclusively on sediment trap data, derived from regression relationships, or reported as wt% organic carbon without accompanying sedimentation rates. The data span a broad range of reservoir areas, ranging from 0.001 km^2 to 5363 km^2, but are skewed toward relatively small reservoirs as compared to those included in the GranD database (Lehner et al., 2011), with a median of 0.62 vs. 5.80 km^2 (Supplementary Information). Of the 37 total reservoirs included, sixteen are $\geq$ 1 km^2; this represents <0.3% of the reservoirs of a similar size class in the GranD database and ~0.1% of those estimated to exist globally (Lehner et al., 2011). These data are representative of both the mean and median latitude of reservoirs in the GranD database, but are heavily weighted to the temperate latitudes of the American Midwest (Figure 1).

Estimated rates of carbon burial in these reservoirs range from 0.23 gC $m^{-2}yr^{-1}$ in Lake Kariba, Zambia/Zimbabwe (Kunz et al., 2011) to 6600 gC $m^{-2}yr^{-1}$ in Englebright Lake, California (USA) (Pondell and Canuel, 2017), a range of five orders of magnitude, with a median of 240 gC $m^{-2}yr^{-1}$ and mean of 750 gC $m^{-2}yr^{-1}$. While Downing and others

(2008) and Mendonça and others (2017) found a negative correlation between carbon accumulation rate and reservoir area, we found a weak relationship at best (p = -0.09440371). For example, the lowest rate of carbon burial in our data was measured in Lake Kariba, which, at 5364 km^2, represents the largest reservoir in the dataset. However, the highest rate of carbon burial was reported from Englebright Lake, which, at 3.3 km^2, falls into the fourth quartile (minimum 3.17 km^2) of the dataset's area distribution. Similarly, in keeping with Ritchie (1989) but departing from the results of others, as discussed above, we found a weak or no relationship between carbon burial rates and 1) watershed area (p = -0.09545119), 2) lake to watershed ratio (p = 0.2319662), 3) latitude (p = 0.1400751), and 4) longitude (0.2589156), the only parameters for which were able to derive complete data.

The range in both estimated global average and reservoir-specific carbon burial rates suggest that the magnitude of global carbon burial in reservoir sediments is poorly constrained. Additionally, the discrepancies in explanatory relationships, discussed above, suggest that we lack a functional, process-based understanding of carbon burial to guide a methodical evaluation of carbon sequestration in reservoirs. How can we explain these discrepancies? Further, how best can we both capitalize on existing knowledge and target new studies to develop a process-based understanding of carbon burial in reservoir sediments? In the sections that follow, we discuss the methods and guiding assumptions used to develop the estimates of carbon burial discussed above, evaluate these assumptions from a process-based perspective, and develop a conceptual model a conceptual model of carbon burial in reservoir sediments to suggest a way forward.

4.4 Assessing burial estimates

Because organic matter forms a discrete fraction of the total sediment in the reservoir, the accumulation of organic matter is inseparable from the dynamics of reservoir sedimentation, which act as a first-order control on the delivery and burial of organic matter within reservoir basins. Thus, whether implicit or explicit, the chosen collection method, density, and distribution of sampling in a study is defined by a conceptual model of the processes governing the spatial and temporal distribution of particulate organic matter and sediment in a reservoir. In order to evaluate the accuracy of estimates of carbon burial in reservoir sediments, therefore, it is necessary to evaluate the assumptions inherent in different study designs against our understanding of the processes governing organic matter sedimentation and storage in reservoir sediments.

4.4.1 Approaches and assumptions

While analytical methods for the measurement of carbon as a sediment fraction are well defined, the sampling design of sediment carbon studies in reservoirs varies widely. In our database, eight reservoir studies were based on single sampling locations, 21 were based on samples collected along a longitudinal transect (i.e., along the thalweg of the former rivers) ranging from two to 16 locations, and eight were calculated from a grid-based design (Table 2). Collection methods varied as well, with studies of seven reservoirs utilizing surficial grab samples, 24 collecting incomplete short cores (i.e., cores which did not penetrate the full thickness of reservoir sediments), and six collecting cores which spanned the full thickness of reservoir sediment accumulation.

Reservoir studies based on single sampling locations inherently assume that the fractional carbon content in reservoir sediments is uniform or quasi-uniform, allowing the extrapolation of results from a single location to the total volume of reservoir sediment (e.g., Downing et al., 2008; Pittman et al., 2013; Clow et al., 2015; Table 2). This premise is rooted in two long-standing models of carbon and sediment distribution in aquatic environments. First, a widely recognized pattern in carbon burial and aquatic sedimentation is the negative correlation between grain size and carbon concentration, a relationship widely observed in shelf environments (c.f. Trask, 1939; Tyson, 1995; Hedges and Keil, 1995). Second, grain size in lakes has been widely cited to vary inversely with depth, suggesting that fine-grained environments are primarily located in the deep-water "depocenters" of reservoirs, where the turbulence-initiated downslope redistribution of fine-grained sediments both homogenizes and focuses sediment in the deepest portion of the lake basin (Håkanson, 1997; Calcagno and Ashley, 1984; Blais and Halff, 1995; Hobbs et al., 2013).

The application of the depocenter paradigm of sedimentation to reservoirs requires the *a priori* assumption that sedimentation processes in reservoirs are dominated by suspended sediment deposition, and resuspension-driven downslope creep, an assumption best applied to small lake basins with simple bathymetry and low shoreline-area ratios. However, reservoirs (or individual reservoir arms) tend to be long and narrow and to have a maximum depth at or near the dam face (c.f. Thornton et al., 1990; Abraham, 1999; Shotbolt et al., 2005). As a result, more common than the depocenter paradigm is the conceptualization of reservoir sediment as varying one dimensionally, i.e., with distance along the former river thalweg. In this paradigm, the reservoir varies evolves from a 'delta and riverine zone', through a 'transition zone,' and into a 'lacustrine zone', resulting in progressively finer-grained sedimentation with distance from the inflow (Thornton et al., 1990; Morris and Fan, 1998). A majority of the carbon burial studies catalogued in our database (57%; Table 2) ascribe to this model; however, the number of sampling sites varies greatly, and, with a few exceptions (e.g., Pondell and Canuel, 2017), tends to be biased toward characterizing the variability of carbon deposition in the lower, finer-grained reservoir reaches, *a priori* assuming that carbon accumulation in the upper, coarse-grained reservoir reaches is negligible.

Finally, in recognition that sedimentation may vary laterally (i.e., perpendicular to the former river thalweg) in addition to longitudinally, many studies utilized a grid-based sampling design to capture the full range of spatial heterogeneity (8 studies; Table 2). Grid-based design is formally based on the assumption that the sample population is distributed randomly across the landscape and that the total range of TOC content in reservoir sediments has an equal chance of collection. Given that TOC deposition and storage is process-controlled and varies systematically in space across a reservoir, this assumption is demonstrably false. However, given the density of sampling, studies utilizing a grid-based design generally represent the most spatially-comprehensive studies of carbon burial commonly undertaken.

While the number and distribution of sampling locations in a reservoir is based on a study's conceptual model of the spatial variability of organic matter distribution, the method of sample collection, which controls the depth of sediment capture, is based on a study's expectations of *temporal* variation. For example, seven of the 37 reservoirs in our database have carbon accumulation rates based on surface samples (~2 to ~ 10 cm depth). This approach assumes that both mineral and organic matter sedimentation are steady or quasi-steady processes and that surface carbon concentrations (QOC_{z_0}) reflect or can be predictably corrected to reflect the long-term burial rate (QOC_{z*}). As with reservoir studies based on a single sample, this approach can be traced to both the depocenter paradigm and the association between fine-grained sediment and carbon concentration, which assume relative homogeneity in sediments as the result of lacustrine fallout and resuspension processes.

However, in recognition that sedimentation varies with time and that surface conditions are not reflective of long-term carbon storage, most studies elect to collect sediments using depth-discrete coring methods (n = 30; Table 2). These range from gravity cores with a typical maximum penetration of about 1 m to piston or other long-core drilling methods, which can capture many meters of sediment. However, because of the considerable added cost and complexity of collecting long cores, long core sampling is relatively rare. As a result, most studies collect depth-discrete but incomplete records of sediment thickness, implicitly assuming that sedimentary and carbon storage processes do not vary beyond the range of conditions captured in shallow cores.

4.4.2 Processes and form

How well do these disparate approaches capture the true distribution of carbon 1) across the range of environments within individual reservoirs and 2) across the population of global reservoirs? Reservoir sedimentation rates and characteristics have been shown to vary with exogenic watershed characteristics, like land use, stream order, stream gradient, and geologic provenance, as well as with endogenic processes like deltaic fallout, turbidity currents, and reservoir operational regimes (cf. Mulholland and Elwood, 1982; Thornton et al. 1990; Morris and Fan, 1998; Abraham, 1999; Ambers, 2001; Keith et al., 2016; Stratton et al., in press). Further, the influence of watershed characteristics like average slope, ecotone, precipitation rates, precipitation seasonality, temperature, and land use have received significant study in the context of inter-reservoir relationship with carbon burial (e.g., Clow et al., 2015). However, few studies have approached the deposition and storage of carbon in reservoir sediments from a process-based perspective.

As discussed above, research concerning carbon content in reservoirs has tended to focus on fine-grained environments, which are primarily located far from reservoir margins and tributary inputs in areas where slackwater conditions create a stable environment conducive to the fallout of suspended sediment and senescent, autochthonous organic matter (the depocenter paradigm). As a result, though it has long been observed that deltaic environments tend to accumulate coarse-grained organic matter ranging from degraded forest litter to coarse woody debris (e.g., Spicer and Wolfe, 1987, Gastaldo, et al., 1987), the prevailing viewpoint has held that while “larger material (> 100 um) may be conspicuous… its contribution to the transported load is generally insignificant” (Tyson, 1995, pg. 213). However, studies suggest that coarse organic material, ranging from 1 mm, degraded phytoclasts to the trunks and rootballs of fallen trees, can be significant to the total carbon load of a reservoir and that its distribution varies systematically in the reservoir (e.g., Pondell and Canuel, 2017; Thothong et al., 2011; Stratton et al., in press).

Complicating the understanding of coarse organic material transport and deposition in reservoirs, however, the irregular shapes of larger organic detritus like leaves, twigs, cones, large seeds, and woody debris tend to influence movement in the traction load, while the variable density of organic matter as a result of its relative saturation allows it to move between suspended and traction load. As a result, while subject to the same processes, the distribution of organic matter in depositional environments is more variable than that of mineral sediment. We thus suggest that the total accumulation of carbon in the sediments of a reservoir cannot be evaluated without also assessing the depositional dynamics of a reservoir.

4.5 Stratigraphic frameworks: connecting form to process

Only three studies in our database provide a spatially explicit discussion of the sedimentologic characteristics associated with carbon burial in the respective reservoirs (Thothong et al., 2011; Kunz et al., 2011; Pondell and Canuel, 2017); of these, only the work of Kunz and others (2011) and of Pondell and Canuel (2017) provide a robust, process-based explanation for the spatial and temporal patterns of carbon burial observed.

The development of a comprehensive predictive model (conceptual or otherwise) of organic matter storage and reservoir sedimentation thus remains speculative for many environments. However, By connecting the physical expression of sediments in depositional environments to 1) the processes which emplaced them, and 2) their evolution in time and space, a stratigraphic approach can provide a robust framework with which to develop an understanding of the controls on carbon burial in reservoir systems. Below, we use a combination of the studies discussed above, our own observations of reservoirs across the Pacific Northwest, and additional literature-based discussions, to develop a conceptual framework of four stratigraphically-distinct reservoir types and the distribution of organic matter within them (Figure 3).

4.5.1 Gilbert Style

First described in deposits of former pluvial lakes in the American West (Gilbert, 1885), Gilbert deltas are characteristic of deposition into freshwater basins in regions with relatively abundant sediment supply and steep gradients, in which the decrease in slope and abrupt expansion of flow decreases the competence of inflow, causing rapid, inertia-based sedimentation (Nemec, 1990a, 1990b). The resulting sediment fall-out tends to produce a tripartite deltaic structure, characterized by coarse-grained, relatively flat topset beds, which progressively prograde over steeply dipping, relatively coarse-grained foreset beds and fine-grained, relatively flat toeset/bottomset beds (Figure 3a). The progradation of Gilbert-style deltas is mostly advanced by high discharge events, which trigger a variety of sediment transport mechanisms ranging from slope creep to catastrophic slope failure (Nemec, 1990b) and which produce a heterogeneous assemblage of stratigraphic units (Stratton et al., in press).

Gilbert style deltas are the “typical” delta as described by most engineering literature concerned with the management of sediment in reservoirs (e.g., Morris and Fan, 1998); however, probably because the deltaic regions are coarse grained, their importance to carbon burial has been generally underappreciated. However, while few studies address the storage of organic material and carbon in Gilbert deltas directly, those that do suggest that carbon storage is disproportionately concentrated in foreset and toeset/prodelta regions of the reservoirs and is primarily derived from in-stream transport of allochthonous, coarse-grained organic matter. This observation is supported by data from both Englebright Lake, an 8.6-km^2 reservoir on the Yuba River in California (USA), and former Lake Mills, a now-removed, 1.3-km^2 reservoir on the Elwha River in Washington (USA) (Pondell and Canuel, 2017; Stratton et al., in press). Both reservoirs, characterized by prominent Gilbert style deltas, were found to have thick accumulations of coarse organic material concentrated in their foreset and toeset beds (Figure 4a); estimates of the carbon content in the foreset beds of former Lake Mills suggest that, despite accounting for only 14% of total sediment deposition in the reservoir, foreset beds store ~30% of the total carbon preserved in the reservoir sediments (Stratton et al., in press). Additionally, isotopic (δ^{13}) analysis completed by Pondell and Canuel (2017) suggested the 50% of the organic matter in Englebright Lake was derived from terrigenous sources, while carbon to nitrogen ratios (a rough proxy for terrestrial vs. aquatic vegetation signatures) in Lake Mills suggested a strong allochthonous input (Stratton et al., in press).

4.5.2 Shoal-water

A second type of reservoir deposit, closely related to the Gilbert delta, is the shoal-water delta (also referred to as a 'mouth bar type' or 'shelf-type') (Figure 3b). Like Gilbert deltas, shoal-water deltas are the product of flow expansion and decreased flow competence created at the head of reservoirs. However, they are more characteristic of deposition into basins with low gradients and shallow water depths and are typically finer-grained than Gilbert deltas, though still rich in fine gravel and sand (Nemec, 1990a; Reading and Collinson, 1996). Shoal-water deltas tend to be characterized by broad, lobate to elongate delta tops that prograde via the deposition of overbank levees and mouth bars, which progressively decrease in grain size with depth and distance from the inflow and appear to store significant volumes of allochthonous organic matter.

For example, a detailed, stratigraphically-based study of former Lake Aldwell, a 1.0-km^2 reservoir located on the Elwha River downstream of former Lake Mills (as discussed above), found that mouth bar and prodelta sands contained large volumes of forest litter and coarse woody debris (Figure 4b), such that 59% of carbon stored in the reservoir was preserved in the delta top/delta slope area, while 23% was preserved in the lakebed (i.e., deepwater basin) portion of the reservoir. Additionally, in Lake Texoma, a 360-km^2 reservoir with normal maximum depth of ~33 m on the border of Texas and Oklahoma (USA), the inflowing Red and Washita Rivers have built extensive lobate to elongate shoal-water deltas several kilometers into the reservoir basin (Hyne, 1978; Olariu and others (2015). While Hyne (1978) found that surface samples from the deltaic regions of the inflow Red and Washita Rivers were relatively rich in carbon as compared to the main lacustrine area of the reservoir, their study did not attempt to describe depth-dependent variation or to calculate a total magnitude of carbon burial. However, they suggest that an average C:N ratios of 11.5 indicates significant terrestrial vs. autochthonous input.

While well-documented in the marine literature (c.f., Reading and Collinson, 1996) and probably quite common globally, shoal-water deltas in reservoirs, and their relationship with carbon burial, appear to have been investigated only rarely. While several reservoirs in our database appear, from satellite or aerial photograph, to be characterized by shoal-water deposits (e.g., Lake Wohlen, Switzerland [Sobek et al, 2009; 2011], Coralville Reservoir [Downing et al., 2008]) the sampling schemes applied do not generally allow us to evaluate these studies from a stratigraphic perspective. In former Lake Aldwell, Stratton and others (in press) interpreted the patterns of sediment and carbon burial observed to be products of both a relatively shallow basin as compared to former Lake Mills upstream and the relatively fine-grained sediment resulting from the upstream impoundment of most bedload by Glines Canyon Dam. Given that few dams occur in isolation but instead are typically components of heavily-dammed river systems (for example, there are 57 reservoirs on the American River and its tributaries upstream of Folsom Reservoir in California [USA]; Minear and Kondolf, 2009), we suggest that reservoirs of this type are probably common and thus rich for further study.

4.5.3 Thalweg

A third style of reservoir sedimentation is defined by the routing of flow and preferential sediment deposition along the inundated former river thalweg, limiting sedimentation in other areas of the reservoir and potentially delivering significant loads of sediment and allochthonous organic material to the dam face (Figure 3c; c.f. Twichell, et al. 2005;). This style of deposition was investigated in detail by Kunz and others (2011) in Lake Kariba, Zambia/Zimbabwe. Using stratigraphic interpretations of cores to develop a conceptual understanding of the flow dynamics in the reservoir, Kunz and others (2011) divided Lake Kariba into two sedimentologically-distinct regions: the former river thalweg, in which turbidity currents produced during flood events were channeled , depositing distinct flood layers that alternate with autochthonous sediments, and the "littoral zones", those areas outside the influence of thalweg-guided turbidity currents and affected only by autochthonous sedimentation. Within the thalweg deposits, Kunz and others (2011) identified alternating "black" (autochthonous) and "bright" (flood) layers, which were distinct in carbon content, total nitrogen, and isotopic carbon ratios, and which, combined with differences in sedimentation rate across four sub-basins, Kunz and others interpreted to show that "sedimentation in Lake Kariba is spatially heterogeneous and flood-dominated."

The preservation of the former Zambezi river thalweg from infill after nearly 50 years of reservoir sedimentation is due to a combination of the size of the reservoir (which, at 5364-km^2, accounts for nearly 2% of the surface area of all reservoirs globally; Downing et al., 2006), and an extremely low sedimentation rate; however, thalweg-style deposition may also be influenced by reservoir operations and dam design. We have observed thalweg-style deposition in our own work at Fall Creek Reservoir, a 6.9-km^2 flood control reservoir in the foothills of the Oregon (USA) Cascades which has been subject to regular, streambed-level drawdowns in addition to its seasonal water surface elevation fluctuation (Keith et al., 2016; Stratton and Keith, unpublished data). Based on detailed reservoir mapping and accompanying stratigraphic sections, the reservoir above its seasonal flood control pool appears to be either erosional or subject to minimal sedimentation, with prominent bedrock exposures in the Fall Creek thalweg and sedimentation on the former flood-plain limited to locally-derived downslope creep and a thin blanket of suspended sediment deposition. Sediment deposition in the lower portion of the reservoir appears to have been concentrated in the thalweg and thalweg-adjacent areas; however, sediment export through a near-streambed outlet gate during a series of annual streambed-level drawdowns begun in water year 2012 now appears to have excavated the thalweg to approximately its pre-dam elevation for nearly its entire length to the dam face.

Our observations of cutbank-exposed sediments along the eroding thalweg of Fall Creek during several drawdown events indicate that reservoir sedimentation in Fall Creek, like Lake Kariba, is dominated by individual discharge events (Figure 4C). However, in contrast to Lake Kariba, coarse organic material appears to comprise a significant fraction of the in-thalweg deposition, with well-sorted sand beds capped by thick (10-20 cm) accumulations of leaf matter, sticks, and general forest litter. These beds appear to be limited to the thalweg. Quantitative estimates of the carbon content of sediments in Fall Creek Reservoir are unavailable; however, in Dorena Lake, a sister flood control reservoir ~25 km southwest of Fall Creek with sedimentation patterns similarly dominated by discharge events, Ambers (2001; unpublished data) measured average, clay-corrected loss on ignition values of 4.9 ± 2.3% (wt%C ~2.86 ± 2.3% assuming a corrective division factor of 1.74) in cores collected from 42 locations across the reservoir but noted that LOI results varied from 1.32 to 16.33%, indicating significant heterogeneity in organic matter deposition.

4.5.4 Lacustrine

Finally, as discussed above, the lacustrine style of deposition is the prevailing paradigm for many studies of carbon deposition in reservoirs, particularly those which are relatively small (Figure 3d). This paradigm appears to be satisfactory in many environments, for example, the low-gradient, agriculturally-dominated reservoirs investigated by Pittman and others (2013), which are dominated by suspended sediment deposition, and the deep-water portions of many larger reservoirs. However, while these reservoirs were investigated with high density sampling in the main portions of the reservoirs, Pittman and others (2013) excluded marginal areas or the inflow-adjacent regions of the reservoir, (implicitly) assuming that carbon content in these regions was minimal. Additionally, as shown by Spicer (1989) in an investigation of Silwood Lake, a 0.013-km^2 reservoir in a wooded, rural area southwest of London, England, accumulation of allochthonous carbon in deltaic regions of small impoundments can be significant over time.

Based on historic maps of the Silwood Lake area and observed progradation rates, Spicer (1989) determined that approximately half of the reservoir's southwestern arm had filled with sediment since its ca. 1815 impoundment; from 1972 to 1975, the delta front was observed to advance at a rate of approximately 1 myr^{-1}. Based on 22 full-length cores plus additional surface sampling from the Silwood Lake delta, Spicer (1989) determined that most sediment was composed of silt with intermittent sandy interbeds, and that allochthonous forest debris was abundant in delta sediments. Using the Sillwood Lake coring data to expand on the delta progradation studies completed by Jopling (1964), Spicer proposed that, in "low energy" lake environments, leaf fragments and other detrital organic matter transported from upstream are deposited at the head of the foreset bed, while unsaturated or partially saturated organic matter may be transported beyond the delta front and into the lacustrine basin. In lakes surrounded by woods, locally-derived (i.e., windblown) leaves may form a second, distinct leaf bed, which is over-ridden by deltaic sedimentation.

The goal of Spicer's (1989) study was to understand leaf deposition in fluviolacustrine environments from a fossilization potential perspective; as such, the study did not the calculate carbon content of sediments in Sillwood Lake beyond describing them as "organic rich." It is thus possible that the detrital organic matter described in Sillwood Lake is conspicuous but unimportant, as discussed above (Tyson, 1995). However, given the importance of detrital organics discussed in other environments, we suggest that allochthonous input to small reservoirs is more important than previously appreciated. Further, most reservoirs are quite young; for example, the four impoundments investigated by Pittman and others (2013) were all about 50 years old at the time of the study. With an approximately 160-year history at the time of the study, the prominence of deltaic sedimentation in Sillwood Lake suggests, with time, small reservoirs may develop a significantly larger allochthonous signature than currently appreciated.

4.6 Discussion

The conceptual models of reservoir sedimentation and carbon burial discussed above suggest that the assumptions inherent in most estimates of carbon burial in reservoirs, both explicit and implicit, local and global, do not hold up in most reservoir environments. True lacustrine-style reservoirs are dominated by suspended sediment deposition and it is possible may thus be adequately characterized by only a few samples. However, while lacustrine zones of larger reservoirs are common, we suggest that lacustrine-style reservoirs with truly uniform sedimentation are probably limited to small farm ponds or non-headwater streams with little bedload and that even small, relatively uniform reservoirs show some variability in carbon storage. For example, Pittman and others (2013) showed that TOC generally increased with distance from the inflow and that lateral gradients varied by a factor of two in four lacustrine-style impoundments ranging from 5 to 25 ha (0.05 to 0.25 km^2). Further, based on a simple random sampling approach, they suggest a sampling frequency of 0.8 samples/ha, or 80 samples/km^2 in "reservoirs of this size," significantly greater than any study we assessed.

Differences between Gilbert-style and shoal-water dominated reservoirs show that, while both are characterized by significant deltaic accumulations of coarse-grained organic matter, shoal-water deltas lack the distinct foreset beds responsible for much carbon storage, instead storing proportionally greater volumes of carbon in the proximal prodelta. In both cases, however, most allochthonous organic matter storage is located toward the head of the reservoirs, decreasing with distance from major inflows. Similarly, the average grain size and overall complexity of bedding appears to be decrease with distance from primary inflows. Given limited resources to sample these types of reservoirs, efforts should thus be made to target the complex, heterogeneous environments in and near the reservoir deltas, which may vary both laterally and with depth according to the stochastic nature of individual discharge events or distributary avulsions. In contrast, the finer-grained environments located further from major inflows can be sampled with less frequency.

In contrast to deltaic reservoirs, thalweg-style reservoirs store most allochthonous carbon in horizontal beds deposited during discharge events within the confining banks of the former river thalweg. Evidence from Fall Creek Reservoir and Lake Mead, the largest reservoir in the United States, suggests that turbidity flows can transport coarse organic matter and sediment tens of kilometers to the dam face (Kostic et al. 2002, Twichell et al. 2005, Wildman et al. 2011; Stratton, unpublished data), while former floodplain areas beyond the thalweg are probably subject only to autochthonous, suspended sediment deposition (Kunz et al., 2001). As a result, sampling in these environments can be designed to primarily target longitudinal variation along thalweg deposits with only supplemental sampling of the relatively homogeneous former floodplain environments.

While a conceptual model of the style of reservoir sedimentation can be used to develop a sampling strategy which maximizes resources to characterize heterogeneous portions of reservoirs, we suggest that every effort should be made to capture or characterize the full depth of reservoir sediments. First, given the three-dimensional nature of sedimentation processes, the relative surface exposure of individual units does not equate to volumetric importance. For example, because of the steep dip and rapid progradation of the overlying topset beds, Gilbert-style foreset beds like those encountered in former Lake Mills or Englebright Lake account for only a small fraction of the sediments exposed at or near the surface of the reservoir bed. However, they represent a volumetrically major portion of reservoir sediment accumulation, and, as discussed above, probably represent the site of significant carbon burial (Figure 3a). Sampling schemes that do not account for this variability with depth and sample only surface or near-surface exposures risk missing a major site of carbon burial in reservoir sediments and significantly underestimating carbon burial.

Second, reservoir sedimentation is likely to evolve over time, both as an intrinsic response to the reduction in accommodation space and in response to external events. For example, given enough time and adequate sediment supply, incised former thalwegs in thalweg-style reservoirs will fill and cease to act as a funnel for turbidity currents, probably causing the reservoir to evolve to a more deltaic-dominated system. Additionally, upstream watershed development or deforestation, landslides, or climate variability may gradually or abruptly increase the rate of sedimentation in reservoir sediments (e.g., Thothong et al., 2011; Bountry et al., 2011). Alternatively, the upstream closure of a dam may abruptly reduce the total volume of sediment entering a reservoir and cause it to be proportionally finer, causing a reservoir to evolve from a Gilbert-style to a shoal-water delta, as in the case of former Lake Aldwell (Stratton et al., in press).

Third, where cores span the entire thickness of reservoir sedimentation, they allow the calculation of an accurate point-based sedimentation rate since dam closure. In reservoirs without accurate pre-dam topographic surveys or accurate bathymetry (a common occurrence; Mendonça et al., 2014), reservoir sedimentation rates, particularly in deltaic regions, can be difficult to determine (e.g., Sobek et al., 2009; Kunz et al.,2011). Isotopic methods common to lacustrine or shelf environments (e.g., ^{210}Pb or ^{137}Cs) may be unreliable due to the variable, coarse-grained nature of deposits in reservoir sediments (Stratton, unpublished data). Geophysical methods that allow characterization of sediment horizons provide the ability to calculate sedimentation rates and understand sediment stratigraphy, but must be depth-calibrated based on sediment cores (c.f. Mendonça et al., 2014).

Finally, while the categorization of reservoir types (Figure 3) is useful as an organizational tool to conceptualize our understanding of carbon storage and the sedimentation processes involved for a suite of different reservoirs, in reality, these classifications are gradational, and tend to vary within a single reservoir according to exogenic watershed influences. For example, Lake Billy Chinook, a 121-km^2 reservoir formed by the 1964 damming of the Deschutes River immediately downstream of its confluence with both the Crooked and Metolius Rivers in central Oregon (USA), is sourced from three watersheds with unique geology, climate, land cover, and upstream impoundment conditions (c.f. O'Connor and Grant, 2003). In a pilot study designed to understand the dynamics of carbon burial as influenced by the variable watershed conditions, down-core averaged measurements of weight percent organic carbon, were relatively similar across the three arms of the reservoir, ranging from means of 2.70 to 4.51 wt% organic carbon (Figure 4A; Stratton, unpublished data).

However, estimated sedimentation rates between the reservoir arms suggested that an approximately 1-m gravity core represented less than one year of accumulation in the Crooked River Arm, which had deposited a significant Gilbert-style delta in the upper reaches of the reservoir, while an approximately 1-m gravity core collected from the Metolius River arm, which had no discernable deltaic sedimentation, probably represented the entire 50-year record of sedimentation. Further, carbon to nitrogen ratios were significantly different across each arm (Figure 4B; $p < 0.001$), suggesting that 1) the importance of autochthonous organic matter varied significantly between reservoir arms and 2) the long-term storage potential of shallowly-buried organic carbon varied significantly between reservoir arms.

4.7 Conclusions

The conceptual models of reservoir sedimentation and carbon burial discussed above suggest that many of the assumptions inherent in most estimates of carbon burial in reservoirs, both explicit and implicit, local and global, do not hold up in most reservoir environments. Reservoirs are complex environments subject to a variety of depositional processes; because detrital organic matter constitutes a fraction of the sediment itself, carbon burial cannot be characterized in the absence of a process-based understanding of the primary depositional processes operating in a given reservoir and their evolution through time. By developing a generalized stratigraphic framework of four types of reservoirs, we create a conceptual model to link form to process and evaluate our understanding of carbon burial dynamics in each. While the individual dynamics of Gilbert style, shoalwater, thalweg, and lacustrine-style reservoirs vary, the sampling designs most common to studies of reservoir and carbon sedimentation appear to be biased to fine-grained sediments, probably resulting in the significant underestimation of organic matter preservation in reservoirs globally.

This uncertainty reveals gaps in our fundamental understanding of depositional processes and complexity of the biogeochemical environments created by reservoirs; as a result, we suggest that the net balance between greenhouse gas production and surface emission and carbon burial remains poorly constrained. Given that respiration (of both CO_2 and CH_4) is inversely related to burial by the rate of carbon supply (eqn 1), knowledge of the dynamics of carbon burial in reservoirs should lead to better understanding of the dynamics of greenhouse gas production and could inform strategies to manage the production of methane vs. carbon dioxide in reservoirs; with at least 3700 hydropower dams >1 MW planned or under construction by 2020 (Zarfl et al., 2015), it presents an urgent management question. Additionally, understanding the dynamics of reservoir and nutrient sedimentation is crucial to managers attempting to control water quality, maximize the hydrologic sustainability of dams, and mitigate the downstream impacts of sediment deprivation or flushing, and provides insight into the interactions between fluvial and slackwater environments in a wide range of natural environments.

4.8 Acknowledgements

We thank David Clow and Rebecca Ambers for providing access to unpublished datasets which contributed greatly to the intellectual development of this work and Rose Wallick and Mackenzie Keith for their insightful discussion. Funding for the collection of data from Lake Billy Chinook was provided as a grant to L. Stratton by the HydroResearch Foundation; we thank Rob Wheatcroft, Miguel Goñi and his REU students, and Ann Morey Ross for their great generosity with their time and equipment in the collection and processing of that data.

4.9 References Cited

Abraham, J., Allen, P.M., Dunbar, J.A., and Dworkin, S.I. (1999). Sediment type distribution in reservoirs: sediment source versus morphometry. *Environmental Geology*, 38, p. 101–110. https://doi.org/10.1007/s002540050406

Abril, G., Guérin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., Tremblay, A., Varfalvy, L., Dos Santos, M. A., and Matvienko, B. (2005). Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana), *Global Biogeochemical Cycles*, 19, GB4007, https://doi.org/10.1029/2005GB002457

Ambers, R.K. (2001). Using the sediment record in a western Oregon flood-control reservoir to assess the influence of storm history and logging on sediment yield. *Journal of Hydrology*, *244(3-4)*, p. 181–200. https://doi.org/10.1016/S0022-1694(01)00331-6

Blair, N.E. and Aller. R.C. (2012). The fate of terrestrial organic carbon in the marine environment. *Annual Review of Marine Science*, 4, 401-423. https://doi.org/10.1146/annurev-marine-120709-142717

Blais, J. M. and Halff, J. (1995). The influence of lake morphometry on sediment focusing. *Limnology and Oceanography*, 40(3), 582-588.

Bountry, J., Ferrari, R., Wille, K., and Randle, T.J. (2011). 2010 Survey Report for Lake Mills and Lake Aldwell on the Elwha River, Washington: United States Department of the Interior Bureau of Reclamation Technical Report SRH-2010-23, 66 p.

Burdige, D.J. (2006). Geochemistry of marine sediments. Princeton, New Jersey: Princeton University Press. 624 pp.

Calcagno, T. H., and Ashley, G. M. (1984). Sedimentation processes in an impoundment, Union Lake, New Jersey. *Environmental Geology and Water Sciences* 6(4), 237-46.

Clow, D. W., Stackpoole, S. M., Verdin, K. L., Butman, D. E., Zhu, Z. L., Krabbenhoft, D. P., and Striegl, R. G. (2015). Organic Carbon Burial in Lakes and Reservoirs of the Conterminous United States. *Environmental Science & Technology*, 49(24), 14741-14741. https://doi.org/ 10.1021/acs.est.5b00373

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Middelburg, J. J., and Melack, J. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems*, 171-184. https://doi.org/10.1007/s10021-006-9013-8

Deemer, B. R., Harrison, J. A., Li, S. Y., Beaulieu, J. J., Delsontro, T., Barros, N., Bezerra-Neto, J. F., Powers, S. M., dos Santos, M. A., and Vonk, J. A., 2016, Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis. *Bioscience*, 66(11), 949-964. https://doi.org/10.1093/biosci/biw117

Downing, J. A., J. J. Cole, J. J. Middelburg, R. G. Striegl, C. M. Duarte, P. Kortelainen, Y. T. Prairie, and K. A. Laube (2008). Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century. *Global Biogeochemical Cycles*, 22, GB1018, https://doi.org/10.1029/2006GB002854

Downing, J.A., Prairie, Y.T., Cole, J.J., Duarte, C.M., Tranvik., L.J., Striegl, R.G., McDowell, W.H., Kortelainen, P., Caraco, N.F., Melack, J.M, Middelburg, J.J. (2006). The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography,* 51(5), 2388-2397. https://doi.org/10.4319/lo.2006.51.5.2388

Drake, T. W., Raymon, P.A., and Spencer, R.G.M. (2017). Terrestrial carbon inputs to inland waters: a current synthesis of estimates and uncertainty. *Limnology and Oceanography Letters* (00), https://doi.org/10.1002/lol2.10055

Gastaldo, R., Douglass, D., & McCarroll, S. (1987). Origin, Characteristics, and Provenance of Plant Macrodetritus in a Holocene Crevasse Splay, Mobile Delta, Alabama. *PALAIOS*,2(3), 229-240. https://doi.org/10.2307/3514673

Gilbert, G.K. (1885). The topographic features of lake shores, in Fifth Annual report of the United States Geological Survey 1883-84, 69-123.

Guérin, F., Abril, G., Richard, S., Burban, B., Reynouard, C., Seyler, P. and Delmas, R. (2006). Methane and carbon dioxide emissions from tropical reservoirs: significance of downstream rivers. *Geophysical Research Letters*, 33, 1-6. https://doi.org/ 10.1029/2006GL027929

Håkanson, L. (1977). The influence of wind, fetch and water depth on the distribution of sediments in Lake Vanern, Sweden. *Canadian Journal of Earth Science* (14),: 397-412.

Hedges, J. I., and Keil, R. G. (1995). Sedimentary organic-matter preservation - an assessment and speculative synthesis. *Marine Chemistry, 49(2-3),* 81-115. https://doi.org/10.1016/0304-4203(95)00008-F

Henrichs, S.M. and Reeburgh, W.S. (1987). Anaerobic mineralization of marine sediment organic matter: rates and the role of anaerobic processes in the oceanic carbon economy. *Geomicrobiology Journal*, 5(3-4). https://doi.org/10.1080/01490458709385971

Hobbs, W.O., Engstrom, D.R., Scottler, S.P., Zimmer, K.D., and Cotner, J.B. (2013). Estimating modern carbon burial rates in lakes using a single sediment sample. *Limnology and Oceanography: Methods*, 11, 316-326. https://doi.org/10.4319/lom.2013.11.316

Hyne, N.J. (1978). The distribution and source of organic matter in reservoir sediments: Environmental *Geology*, *2(5),* 279-287. https://doi.org/10.1007/BF02430674

Jacinthe, P. A., Filippelli, G. M., Tedesco, L. P., and Raftis, R. (2012). Carbon storage and greenhouse gases emission from a fluvial reservoir in an agricultural landscape. *Catena,* 94, 53-63. https://doi.org/10.1016/j.catena.2011.03.012

Jopling, A. V., 1964, Interpreting the concept of the sedimentation unit. Journal of Sedimentary Petrology 34, 165-172.

Keith, M.K., Wallick, J.R., Taylor, G., Mangano, J., White, J. and Schenk, L. (2016). Geomorphic responses of gravel bed rivers to fine sediment releases during annual reservoir drawdowns: Spatial patterns and magnitude of aggradation along Fall Creek and Middle Fork Willamette River, Oregon. Abstract EP53C-0984 presented at 2016 Fall Meeting, AGU, San Francisco, California, 12-16 December.

Kostic, S., Parker, G., and Marr, J.G. (2002). Role of turbidity currents in setting the foreset slope of clinoforms prograding into standing fresh water. *Journal of Sedimentary Research*, 72, 353–362.

Kunz, M. J., Wuest, A., Wehrli, B., Landert, J., and Senn, D. B. (2011). Impact of a large tropical reservoir on riverine transport of sediment, carbon, and nutrients to downstream wetlands. *Water Resources Research, 47(12)*, W12531, https://doi.org/10.1029/2011WR010996..

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N. and Wisser, D. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, 9,: 494–502. https://doi.org/10.1890/100125

Maavara, T., Lauerwald, R., Regnier, P. and Van Capellen, P. (2017). Global perturbation of organic carbon cycling by river damming. *Nature Communications, 8,* https://doi.org/0.1038/ncomms15347

Mendonça, R., Kosten, S., Sobek, S., Cardoso, S. J., Figueiredo-Barros, M. P., Estrada, C. H. D., and Roland, F. (2016). Organic carbon burial efficiency in a subtropical hydroelectric reservoir: *Biogeosciences,* 13(11), 3331-3342. https://doi.org/10.5194/bg-13-3331-2016

Mendonça R, Kosten S, Sobek S, Barros N, Cole JJ, Tranvik L, Roland F. (2012). Hydroelectric carbon sequestration. *Nature Geoscience,* 5(12), 838–40. https://doi.org/10.1038/ngeo1653

Mendonça, R, Müller, R.A., Clow, D., Verpoorter, C., Raymond, P., Tranvik, L.J., and Sobek, S. (2017). Organic carbon burial in global lakes and reservoirs. Nature Communications, 8(1694), https://doi.org/10.1038/s41467-017-01789-6 | www.nature.com/naturecommunications

Mendonça, R., Kosten, S., Sobek, S., Cole, J. J., Bastos, A. C., Albuquerque, A. L., Cardoso, S. J., and Roland, F. (2014). Carbon Sequestration in a Large Hydroelectric Reservoir: An Integrative Seismic Approach. *Ecosystems,* 17(3), 430-441. https://doi.org/10.1007/s10021-013-9735-3

Minear, J.T., and Kondolf, G.M. (2009). Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California: TECHNICAL NOTE. *Water Resources Research*, 45, https://doi.org/10.1029/2007WR006703.

Morris, G. L., and Fan, J. (1998), Reservoir Sedimentation Handbook, New York, New York: McGraw-Hill, 898 pp.

Mulholland, P.J. and Elwood, J.W. (1982). The role of lake and reservoir sediments as sinks in the perturbed global carbon cycle. *Tellus*, 34(5), 490-499, https://doi.org/10.1111/j.2153-3490.1982.tb01837.x

Nemec, W., 1990a, Deltas – remarks on terminology and classification, in: Collela, A. and Prior, D.B. (eds), Coarse-grained deltas. Special Publication Number 10 of the International Association of Sedimentologists, Blackwell Scientific Publications, Boston, p. 3 – 12.

Nemec, W., 1990b, Aspects of sediment movement on steep delta slopes, in: Collela, A. and Prior, D.B. (eds), Coarse-grained deltas. Special Publication Number 10 of the International Association of Sedimentologists, Blackwell Scientific Publications, Boston, p. 29 – 74.

Némery, J., Gratiot, N., Doan, P.T.K., Duvert, C., Alvarado-Villanueva, R, and Duwig, C. (2016). Carbon, nitrogen, phosphorus, and sediment sources and retention in a small eutrophic tropical reservoir. *Aquatic Sciences*, 78, 171-189. https://doi.org/0.1007/s00027-015-0416-5

Nilsson, C. Reidy, C.A., Dynesius, M. and Revenga, C. (2005). Fragmentation and flow regulation of the world's large river systems. *Science,* 305, 405-408. https://doi.org/10.1126/science.1107887

O'Connor, Grant, G.E., and Haluska, T.L. (2003). Overview of geology, hydrology, geomorphology, and sediment budget of the Deschutes River Basin, Oregon. In J.E. O'Connor, G.E. Grant (Eds.), A peculiar river: geology, geomorphology, and hydrology of the Deschutes River, Oregon, Water Science and Application (Vol. 7, pp. 7-30). Washington, DC: American Geophysical Union.

Olariu, C., Bhattacharya, J. P., Leybourne, M.I., Boss, S., and Stern, B. (2015). Interplay between river discharge and topography of the basin floor in a hyperpycnal lacustrine delta. *Sedimentology*, 59(2), 704-728.

Pittman, B., Jones, J.R., Millspaugh, J.J., Kremer, R.J., and Downing, J.A. (2013). Sediment organic carbon distribution in 4 small northern Missouri impoundments: implications for sampling and carbon sequestration, *Inland Waters*, 3, 39-46. https://doi.org/0.5268/IW-3.1.507

Pondell, C.R. and Canuel, E.A. (2017). The role of hydrodynamic sorting on the accumulation and distribution of organic carbon in an impoundment: Englebright Lake, California, USA: *Biogeochemistry*, 133(2), 129-145. https://doi.org/10.1007/s10533-017-0319-8

Reading, H.G. and Collinson, J.D., 1996, Clastic Coasts, in: Sedimentary Environments: Processes, Facies and Stratigraphy Reading, H.G. (ed.), Sedimentary Environments: Processes, Facies and Stratigraphy (third edition), Oxford : Blackwell Science, p. 154-231.

Ritchie, J C. and McHenry, J.R. (1977). The Distribution of Cs-137 in Some Watersheds in the Eastern United States. *Health Physics, 32,* 101-105.

Ritchie, J. C., 1989, Carbon content of sediments of small reservoirs. *Journal of the American Water Resources Association*, 25(2), 301-308. https://doi.org/10.1111/j.1752-1688.1989.tb03065.x.

Ritchie, J. C., Gill, A. C. and McHenry, J. R. (1975). A comparison of nitrogen, phosphorus, and carbon in sediments and soils of cultivated and non-cultivated watersheds in the North Central States. *Journal of Environmental Quality,* 4, 339-341.

Shotbolt, L.A., Thomas, A.D., and Hutchinson, S.M. (2005). The use of reservoir sediments as environmental archives of catchment inputs and atmospheric pollution. *Progress in Physical Geography,* 29(3), 337-361. https://doi.org/10.1191/0309133305pp452ra

Snyder, N. P., Wright, S. A., Alpers, C. N., Flint, L. E., Holmes, C. W., and Rubin, D. M. (2006). Reconstructing depositional processes and history from reservoir stratigraphy: Englebright Lake, Yuba River, northern California. *Journal of Geophysical Research-Earth Surface*, 111(F4). https://doi.org/10.1029/2005JF000451

Snyder, N.P., Rubin, D.M., Alpers, C.N., Childs, J.R., Curtis, J.A., Flint, L.E., and Wright, S.A. (2004), Estimating accumulation rates and physical properties of sediment behind a dam: Englebright Lake, Yuba River, northern California. *Water Resources Research*, 40, https://doi.org/10.1029/2004WR003279.

Sobek S., Durisch-Kaiser E., Zurbrugg R., Wongfun N., Wessels M., Pasche N., and Wehrli, B. (2009). Organic carbon burial efficiency in lake sediments controlled by oxygen exposure time and sediment source. *Limnology and Oceanography*, 54, 2243–2254, https://doi.org/10.4319/lo.2009.54.6.2243

Sobek, S. R., R. Zurbrügg, and Ostrovsky, I. (2011). The burial efficiency of organic carbon in the sediments of Lake Kinneret, *Aquatic Science*, 73, 355–364, https://doi.org 10.1007/s00027-011-0183-x.

Spicer, R.A. (1989). The formation and interpretation of plant fossil assemblages, *in* Callow, J.A. (Ed.), *Advances in Botanical Research,* 16, 96-150. San Diego, California: Academic Press, Inc.

Spicer, R.A., and Wolfe, J.A. (1987). Plant taphonomy of late Holocene deposits in Trinity (Clair Engle) Lake, northern California. *Paleobiology*, 13(2), 227–245.

St. Louis, V.L., Kelly, C.A., Duchemin, E., Rudd, J.W.M., and Rosenberg, D.M. (2000). Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate, *Bioscience*, 50(9), 766-775. https://doi.org/10.1021/es001924p

Stratton, L.E. and Grant, G.E. (in press). *Autopsy of a reservoir: facies architecture in a multi-dam system, Elwha River, Washington, USA*, GSA Bulletin.

Syvitski, J.P., Vörösmarty, C.J., Kettner, A.J., and Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, 308(5720), 376-380. https://doi.org/10.1126/science.1109454

Thonton, K.W., Kimmel, B.L., and Payne, F.E. (1990). *Reservoir Limnology: ecological* perspectives. Somerset, New Jersey: John Wiley & Sons, Inc.

Thothong, W., Huon, S., Janeau, J., Boonsaner, A., de Rouw, A., Planchon, O., Bardoux, G., and Parkpian, P. (2011). Impact of land use change and rainfall on sediment and carbon accumulation in a water reservoir of North Thailand, *Agriculture, Ecosystems and Environment*, 140, 521-533. https://doi.org/10.1016/j.agee.2011.02.006

Tranvik, L.J., Downing, J.A., Cotner, J.B., Loiselle, S.A., Striegl, R.G., Ballatore, T.J., Dillon, P. Finlay, K., Fortino, K., Knoll, L.B., Kortelainen, P.L., Kutser, T., Larson, S., Laurion, I., Leech, D.M., McCallister, S.L., McKnight, D.M., Melack, J.M., Overholt, E., Porter, J.A., Sobek, S., Tremblay, A., Vanni, M.J., Verschoor, A.M., von Wachenfeldt, E. and Weyhenmeyer, G.A. (2009). Lake and reservoirs as regulators of carbon cycling and climate, *Limnology and Oceanography*¸56 (6, part 2), 2298-2314. . https://doi.org/10.4319/lo.2009.54.6_part_2.2298

Trask, P.D. (1939). Organic content of recent marine sediments, in Trask, P.D. (Ed.), *Recent Marine Sediments*.Tulsa, Oklahoma: American Association of Petroleum Geologists, p. 428-453.

Twichell, D.C., Cross, V.A., Hanson, A.D., Buck, B.B., Zybala, J.G., and Rudin, M.J. (2005) Seismic architecture and lithofacies of turbidites in Lake Mead (Arizona and Nevada, U.S.A.), an analog for topographically complex basins. *Journal of Sedimentary Research*, 75(1), 134-148.

Tyson, R.V. (1995). Sedimentary organic matter: organic facies and palynofacies: New York, Chapman & Hall, 615 p.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P. and Syvitski, J.P.M. (2003). Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change*, 39, 169-190. https://doi.org/10.1016/S0921-8181(03)00023-7

Wetzel, R. G. (2001). Limnology: Lake and River Ecosystems, 3rd ed., London: Academic Press, Elsevier, 1006 p.

Wildman, R.A., Pratson, L.F., DeLeon, M., and Hering, J.G. (2011). Physical, Chemical, and Mineralogical Characteristics of a Reservoir Sediment Delta (Lake Powell, USA) and Implications for Water Quality during Low Water Level. *Journal of Environment Quality*, 40(2), 575-586. https://doi.org/10.2134/jeq2010.0323

Zarfl, C., Lumsdon, A., Berlekamp, J., Tydecks, L. & Tockner, K. (2015). A global boom in hydropower dam construction, *Aquatic Sciences*, 77, 161–170. https://doi.org/10.1007/s00027-014-0377-0

4.10 Figures

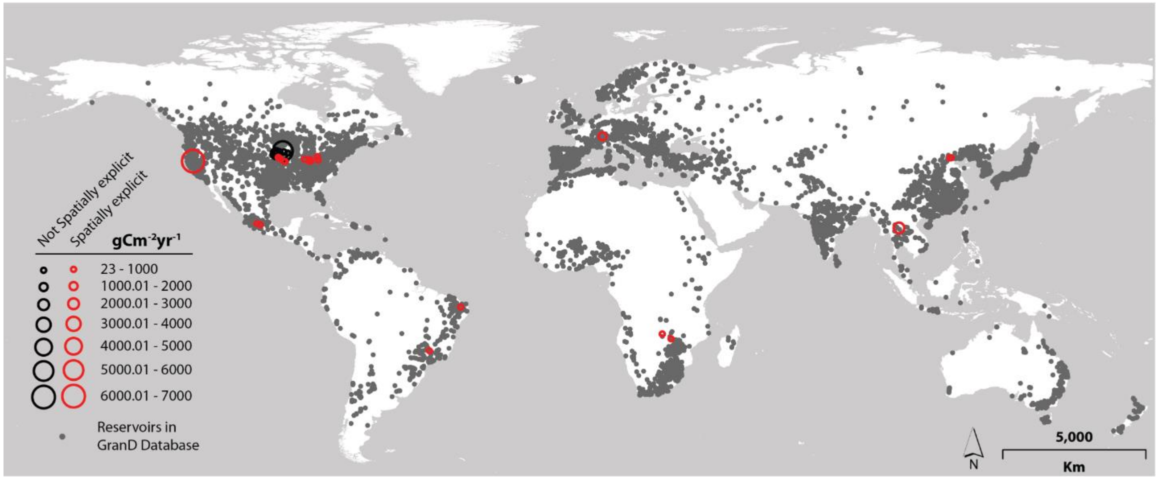


Figure 4-1. Area-weighted estimates of carbon burial in sediments of individual reservoirs included in Table 2 (open circles) vs. global distribution of dams in GranD Database (dots; Lehner et al., 2011). Size of open circles are keyed to burial rate; black circles represent estimates derived from one sample per reservoir and red circles represent spatially-explicit estimates.

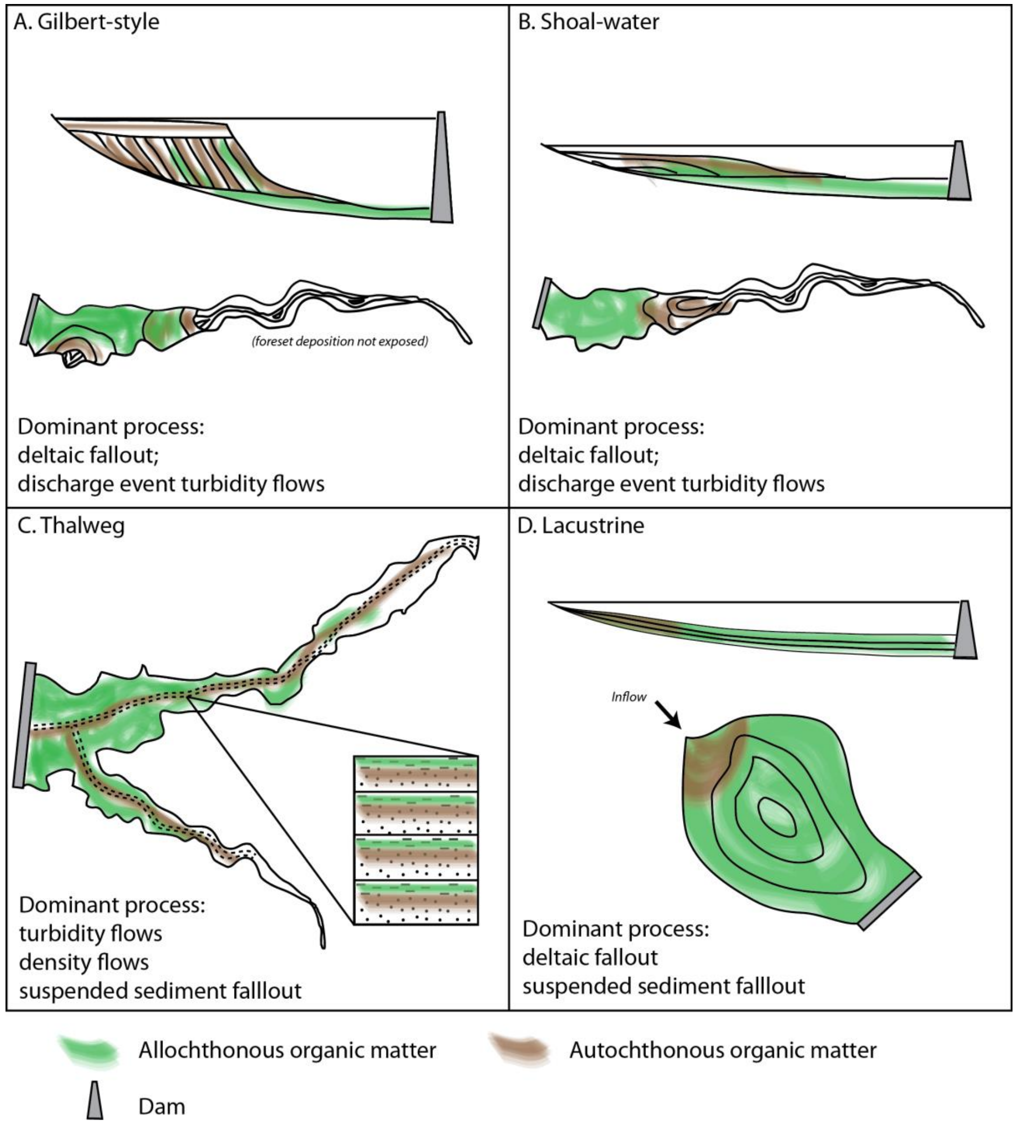


Figure 4-2. Conceptual stratigraphic framework of four ‘typical’ reservoir types.

Figure 4-3. Examples of coarse organic matter deposition in A) Lake Mills (Elwha River), showing prodelta sands (A1), foreset beds (A2), B) Lake Aldwell (Elwha River), showing delta mouthbar sands (B1 and B2) and C) Fall Creek Reservoir (Fall Creek), showing horizontally-laminated coarse organic matter along Fall Creek thalweg. Streambed-level outlet gate on Fall Creek Dam is visible in rear of Photo C1.

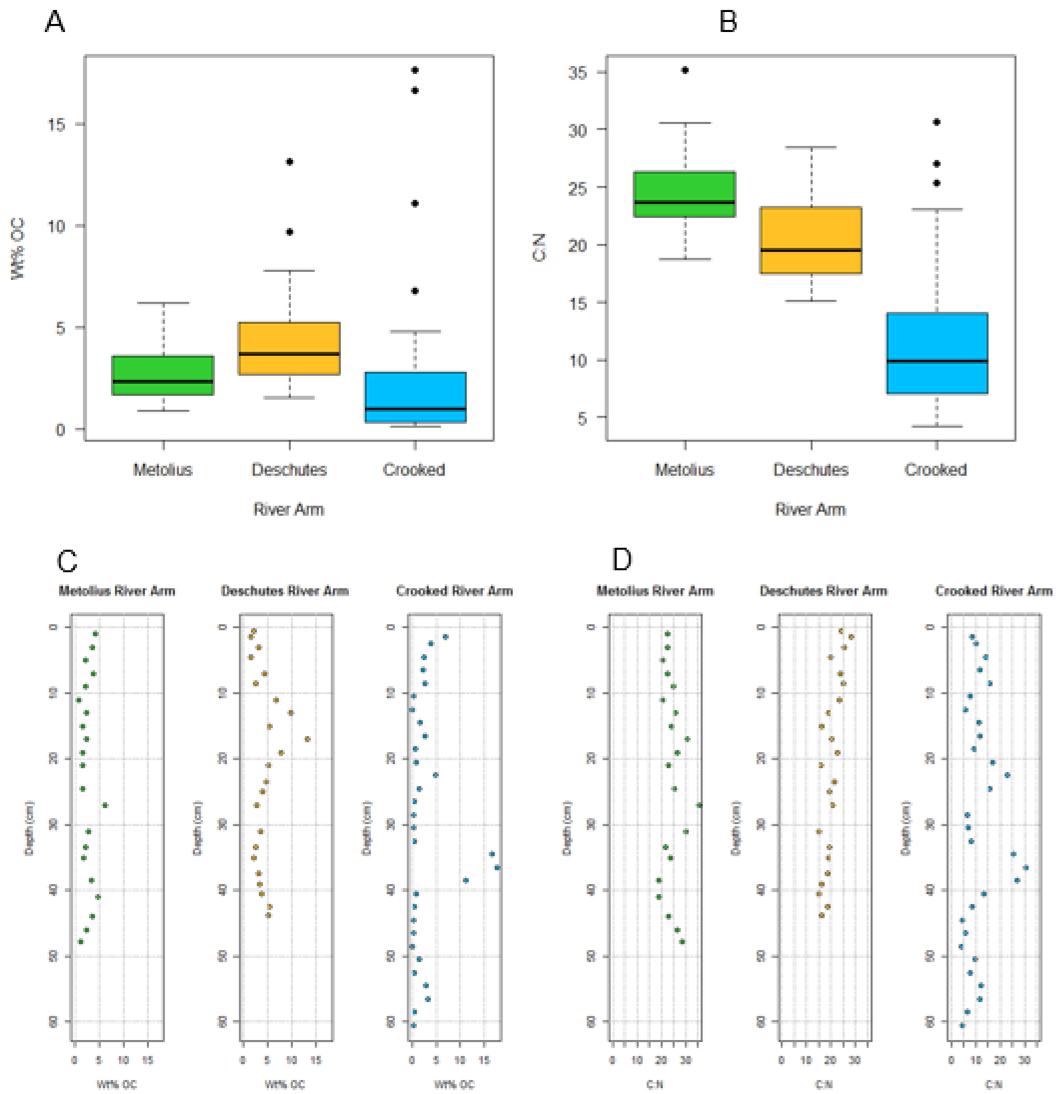


Figure 4-4. Total organic carbon and C:N ratios in cores collected from Lake Billy Chinook. A) Boxplot of average wt% TOC compared among three reservoir arms. B) Boxplot of average C:N ratios of cores collected from three arms. All arms are statistically different. C) and D) down-core profiles of wt% TOC and C:N ratios.

4.11 Tables

Reference	US Total (Pg C/yr)	Global Total (Pg C/yr)	Normalized (g C/m^2/yr)	Method	Notes
Mulholland and Elwood, 1982	0.018 - 0.024	0.2	500 (350 in US)	Assumed 1.5 wt% OC (Ritchie et al., 1975; Ritchie and McHenry, 1977). US estimate based on reservoir area of 60,000 km^2 (Martin and Hanson, 1966); global based on reservoir area of 400,000 km^2 (Frey, 1967)	Estimates as high as 980 g C/m^2/yr for Asia; authors note that total global estimate is probably conservative
Ritchie, 1989		0.2 - 0.3	675 ± 739	Primary data from 58 reservoirs	97% of reservoirs in dataset <0.5 km^2; spatially biased to Midwest and Texas. Note high variability in OC content, OC accumulation, and sediment accumulation rates.
Dean and Gorham, 1998		0.16	400	Assumed 2 wt% OC (Mulholland and Elwood, 1982; Ritchie, 1989), 1 g/cm^3 bulk density, 2 cm/yr sedimentation rate (Mulholland and Elwood, 1982)	Based on reservoir area of 400,000 km^2 (Shiklomanov, 1993). Attribute high burial to relatively low OC and high sedimentation.
Stallard, 1998		0.29	400*	Scenario-based model based on calculated sediment volumes. Assumed 1.9 wt% OC and 0.95x10^6 g/m^3 density (Ritchie, 1989) clastic (i.e., allochthonous) deposition	Includes autochthonous production in model inputs
Cole et al., 2007		0.18	400	Midpoint of Dean and Gorham (1998), Mulholland and Elwood (1982)	Rased on reservoir area of 400,000 km^2 (Dean and Gorham, 1998)
		0.6			Based on reservoir area of 1,500,000 km^2 (St. Louis et al., 2000)
Downing et al. 2008		0.15 (farm ponds only)	2122 (148 - 17,392)	Regression model based on single sample LOI from 16 farm ponds and eutrophic small reservoirs in Iowa. Small agricultural ponds estimated as >75,000 km^2 globally.	Note that extrapolation to world reservoir values is speculative but suggest value of 1,000 g C/m^2/yr
Clow et al., 2015	0.0082 (0.0066 - 0.0102)		149 - 363	Regression analysis of wt% TOC and reservoir sedimentation; data from US Environmental Protection Agency (2009); RESSED database (United States Geological Survey, 2013)	Explicitly excludes farm ponds. Clow et al. (2015) attribute smaller estimate as compared to Dean and Gorham (1998) and Mulholland and Elwood (1982) to lower calculated sedimentation rates
Mendonca et al., 2017		0.06	144	Literature values of whole-system burial rates (gC/m^2/yr; n = 58) multiplied by estimated global reservoir area ~354,000 km^2	Heavily weighted by eutrophic farm pond data of Downing et al. (2008)
Maavara et al., 2017		0.026 ± 0.0009	80**	Spatially-explicit mass-balance model	Estimate is for year 2000; based on reservoirs in GranD database (Lehner et al., 2011)

*Area-normalized rate calculated using global surface area of 109 m^2 as reported in Table 2 of Stallard (1998)

**Area-normalized rate calculated using reported total annual accumulation divided by 325,723 km^2 (reservoir area as reported by Lehner et al., 2011)

Table 4-1. Continental- and global-scale estimates of carbon burial in reservoir sediments. All data reported as in literature (some units converted for consistency) except where noted. Ranges in parentheses where given in primary literature.

		Count*	Example	Typical Assumptions	Limitations
Sampling method					
Temporal variation (steadiness)	Sediment traps	Excluded	de Junet et al., 2009; Thothong et al., 2011 (supplementary to coring)	Mineral + organic matter sedimentation rate is steady or quasi-steady	Susceptible to influence by resuspension; not suitable for extrapolation beyond deployment periods
	Surface samples	7**	Pittman et al., 2011	Mineral + organic matter sedimentation rate is steady or quasi-steady	Does not capture heterogeneity from event-based sedimentation, delta progradation, long-term evolution of sediment conditions, or drawdown-redistribution of sediment below depth of capture
	Incomplete core	24	Sobek et al., 2009	Sampling depth is representative of full range of depth-dependent heterogeneity below depth of penetration	May not capture heterogeneity from event-based sedimentation, delta progradation, long-term evolution of sediment conditions, or drawdown-redistribution of sediment below depth of capture
	Complete core	6	Pondell and Canuel 2017	Sampling depth captures full range of depth-dependent (time-based) heterogeneity	Total depth penetration often assumed; expensive and logistically demanding beyond ~ 1 m depth (maximum capability of gravity coring)
Sampling distribution (density)					
Spatial variation (uniformity)	Single sample or few samples	8	Downing et al., 2008; Clow et al., 2015 (NLA data)***	Carbon burial as a fraction of sedimentation (i.e., wt% OC) is uniform or quasi-uniform	Wt% OC tends to vary spatially as a function of source and depositional processes
	Longitudinal (thalweg-parallel) transect	21	Kunz et al., 2011a, 2011b; Mendonça et al., 2014; Pondell and Canuel, 2017	Carbon burial as a fraction of sedimentation (i.e., wt% OC) is uniform across the lateral axis of the reservoir; sampling locations capture full range of longitudinal variation	Density current-driven sedimentation tends to follow thalweg; resuspension most important in shallow areas; close spacing necessary to capture influence of tributaries
	Grid-based	8	Thothong et al., 2011; Pittman et al., 2013	Grid density is adequate to capture range of variation	Prohibitively expensive in large reservoirs; statistically-based grid spacing may not capture heterogeneity well

*Included in database; others excluded as noted
**Four informed by additional depth-inclusive sampling
***Discussed in text but not included in database (no burial rates; wt% OC only)

Table 4-2. Categorization of typical assumptions and limitations by sampling method and sampling distribution. Counts represent reservoirs from database in Supplementary Information.

4.12 Supplementary Information

Reference	Reservoir	Lat	Long	Given Location	Wt% C as reported	Wt% OC	Org C accumulation rate as reported	OC Accumulation Rate (gC $m^2 yr^{-1}$)	Sedimentation Rate	Sed rate unit	Area as given	Area (km2)	Continent	Wt%N	C method	C:N	Completion Date	bulk density	Bulk density units	Volume (km3)	Trophic Status	Watershed Area	watershed:lake area
Pittman et al. 2013	Jamesport	39.9977	-93.8425	Missouri	4.88 (0.65 to 7.92)	4.88	183	183	0.97	cm/yr	0.12	0.12	North America	0.506	CN element analysers	ND		ND	NA			88	733
Pittman et al. 2013	Fayette	39.1651	-92.7304	Missouri	2.00 (1.39 to 2.67)	2	229	229	2.47	cm/yr	0.24	0.24	North America	0.22	CN element analysers	ND		0.43	g/cm3			11	46
Pittman et al. 2013	Lick Creek	39.1509	-92.3857	Missouri	4.07 (1.78 to 6.98)	4.07	256	256	1.64	cm/yr	0.05	0.05	North America	0.413	CN element analysers	ND		ND	NA			ND	
Pittman et al. 2013	Worth County	40.4007	-94.5261	Missouri	4.40 (1.59 to 5.83)	4.4	279	279	1.57	cm/yr	0.08	0.08	North America	0.445	CN element analysers	ND		ND	NA			0.1	1
Kunz et al., 2011a	Kariba	-16.5222	28.7616	Zambezi River, Zambia/Zimbabwe			23 (19 to 150)	23	0.07 g, ~10 cm/yr in the deltas	g/cm2/yr	5364	5364	Africa		CN element analyser		1958			157	oligotrophic	667000	124
Kunz et al., 2011b	Itehzi Tehzi	-15.0213	26.0213	Kafue River (Zambezi tributary)	4.8	4.8	62	62	900	g/m2/yr	364	364.00	Africa		CN element analyser	11 to 12	1978	See data		5.4	oligotrophic		
Almeida et al. 2016	ESEC	-6.5809	-37.2558	Brazil	5.6 ± 0.8	5.6	161 (88 to 280)	161	0.5	cm/yr	0.20	0.20	Europe	ND	CN element analysers	ND	69 years in 2014	ND	NA	160000 m3	eutrophic	6	30
Carnero-Bravo et al. 2015	Valle de Bravo	19.2075	-100.1804	Mexico	Graphed only; >2		216 (122 to 380) total; 122-266 (avg 175) 1949 - 1991; 250 (173 to 380) 1991 to 2006.	216	0.12 to 0.56 g/cm2/yr		18.55	18.55	North America	ND	CN element analysers	4 to 8	1947	See Table	g/cm3	0.391	eutrophic	547	29
Downing et al. 2008	Coralville Reservoir	41.7247	-91.5310	Iowa	0.42%	0.42	148	148	992000	m3/yr	19.83	19.83	North America	ND	LOI; converted to g C assuming 47%			681	kg/m3		Eutrophic	7900	398
Downing et al. 2008	Swan Lake	42.0336	-94.8411	Iowa	5.35%	5.35	353	353	3950	m3/yr	0.526	0.526	North America	ND	LOI; converted to g C assuming 47%			881	kg/m3		Eutrophic	3.1	6
Downing et al. 2008	Lake Wapello	40.8214	-92.5702	Iowa	6.85%	6.85	508	508	16400	m3/yr	1.153	1.153	North America	ND	LOI; converted to g C assuming 47%			521	kg/m3		Eutrophic	20.2	18
Downing et al. 2008	Don Williams Lake	42.1113	-94.0180	Iowa	4.69%	4.69	755	755	17900	m3/yr	0.615	0.615	North America	ND	LOI; converted to g C assuming 47%			554	kg/m3		Eutrophic	83.7	136
Downing et al. 2008	Union Grove Lake	42.1243	-92.7197	Iowa	4.55%	4.55	958	958	14800	m3/yr	0.478	0.478	North America	ND	LOI; converted to g C assuming 47%			686	kg/m3		Eutrophic	27.9	58
Downing et al. 2008	Prairie Rose Lake	41.6004	-95.2281	Iowa	3.90%	3.9	2862	2862	43900	m3/yr	0.882	0.882	North America	ND	LOI; converted to g C assuming 47%			1474	kg/m3		Eutrophic	18.5	21
Downing et al. 2008	Springbrook Lake	41.7754	-94.4661	Iowa	4.93%	4.93	1111	1111	2010	m3/yr	0.069	0.069	North America	ND	LOI; converted to g C assuming 47%			767	kg/m3		Eutrophic	4.9	174
Downing et al. 2008	Lower Pine Lake	42.3664	-93.0784	Iowa	4.18%	4.18	5771	5771	28900	m3/yr	0.263	0.263	North America	ND	LOI; converted to g C assuming 47%			1256	kg/m3		Eutrophic	39.2	176
Knoll et al. 2014	Preble	39.7700	-84.6800	USA (midwest)	2.78%	2.78	46.7	46.7	0.41	cm/yr	0.001	0.001	North America	0.37	CN element analysers	8.91	2000	0.41	g/cm3		ND	0.004	4
Knoll et al. 2014	Supply ERC	39.5285	-84.7235	USA (midwest)	3.50%	3.5	49.9	49.9	0.46	cm/yr	0.003	0.003	North America	0.45	CN element analysers	9.11	1996	0.31	g/cm3		ND	0.016	5
Knoll et al. 2014	Rush Run	39.5951	-84.6107	USA (midwest)	3.13%	3.13	53.7	53.7	0.52	cm/yr	0.21	0.21	North America	0.49	CN element analysers	5.89	1970	0.33	g/cm3		ND	4.65	22
Knoll et al. 2014	Pleasant Hill	40.6253	-82.3257	USA (midwest)	2.43%	2.43	104.1	104.1	2.43	cm/yr	3.17	3.17	North America	0.28	CN element analysers	11.17	1933	0.42	g/cm3		ND	516.70	163
Knoll et al. 2014	Miami Whitewater	39.2568	-84.7422	USA (midwest)	1.91%	1.91	160.9	160.9	1.62	cm/yr	0.30	0.30	North America	0.3	CN element analysers	8.75	1968	0.52	g/cm3		ND	3.72	12
Knoll et al. 2014	Four Mile Pond #10	39.6110	-84.7431	USA (midwest)	1.89%	1.89	209.2	209.2	2.05	cm/yr	0.030	0.300	North America	0.22	CN element analysers	10.22	2000	0.54	g/cm3		ND	1.37	5
Knoll et al. 2014	Four Mile Pond #9	39.6091	-84.7326	USA (midwest)	1.89%	1.89	238.8	238.8	2.43	cm/yr	0.040	0.040	North America	0.37	CN element analysers	5.89	1995	0.52	g/cm3		ND	3.18	80
Knoll et al. 2014	Four Mile Pond #14	39.6081	-84.7583	USA (midwest)	1.87%	1.87	291.3	291.3	2.64	cm/yr	0.009	0.009	North America	0.18	CN element analysers	12.14	1998	0.59	g/cm3		ND	1.14	127
Knoll et al. 2014	Winton Woods	39.2598	-84.5138	USA (midwest)	2.37%	2.37	344.8	344.8	2.91	cm/yr	0.71	0.71	North America	0.35	CN element analysers	7.43	1951	0.5	g/cm3		ND	74.07	104
Knoll et al. 2014	Sharon Woods	39.2843	-84.3891	USA (midwest)	2.66%	2.33	563.0	563.0	4.07	cm/yr	0.14	0.14	North America	0.35	CN element analysers	8.75	1939	0.52	g/cm3		ND	12.48	89
Knoll et al. 2014	Strimple	39.2463	-84.7296	USA (midwest)	2.19%	2.19	802.0	802.0	6.91	cm/yr	0.020	0.020	North America	0.31	CN element analysers	8.22	1994	0.53	g/cm3		ND	4.12	173
Vanni et al. 2011	Burr Oak	39.5426	-82.0562	USA (midwest)	1.71%	1.71	50.3	50.3	0.7	cm/yr	2.78	2.78	North America	0.21	CN element analysers	7.94	1950	0.42	g/cm3		ND	85.80	31
Vanni et al. 2011	Acton	39.5590	-84.7365	USA (midwest)	2.14%	2.14	290.7	290.7	2.09	cm/yr	2.40	2.40	North America	0.23	CN element analysers	7.27	1955	0.65	g/cm3		ND	259.34	108
Nemery et al. 2016	Cointzio Reservoir	19.622	-101.256	southern Mexican Central Plateau	10.6 (1.1) mg/g	10.6	83±19	83	2.5±0.5	cm/yr	6 km2	6.00	North America	0.9 (0.1) mg/g	CHN analysis	11 (1)	1940	550 kg/m3 est		0.066	eutrophic	630	105
Zhao et al. 2016	Huairou Reservoir	40.3186	116.6136	Beijing region	1.57 ± 0.63 (0.7 to 2.97)	1.57	62.3 (36.4 to 129.9)	62.3	Reported as thickness only		12.00	12.00	Asia	0.19	CN element analysers	10.8	1958	0.91	g/cm3	0.14	ND	525	44
Zhao et al. 2016	Shisanling Reservoir	40.2556	116.2689	Beijing region	1.72 ± 0.63 (0.69 to 2.77)	1.72	100.1 (33.4 to 230.5)	100.1	Reported as thickness only		3.11	3.11	Asia	1.5	CN element analysers	13.2	1958/1990s	0.97	g/cm3	0.073	ND	223	72
Jacinthe et al. 2012	Eagle Creek	39.8224	-86.3042	central Indiana	3.72 (as 37.2 g C/kg)	3.72	2.3-2.9 Mg C/ha/yr	260	1.57 ±0.4	cm/yr	5.5	5.5	North America	ND	LOI/2.44 (Jacinthe et al., 2010)	ND	36 in 2003	0.51 ± 0.14	g/cm3	29.5x10^6 m3	eutrophic	423	77
Mendonca et al. 2014	Mascarenhas de Moraes	-20.2867	-47.0640	Brazil	2.3 ± 0.5	2.3	42.2	42.2	0.51	cm/yr	272.00	272.00	South America		CN element analysers	10.7	1957				oligotrophic	68522	252
Pondell and Canuel 2017	Englebright	39.24	-121.2692	Yuba River, CA	No lake avg reported; area only		6.6 kg/m2/yr	6600				3.3	North America				1940			0.086		2870	870
Tothong et al. 2011	Mae Thang	18.2210	100.3193	Phrae province, Thailand	Rainy season 1.37 ±0.36; Dry season 2.96 ±0.74; coarse sed 2.31		23.8 Mg C/ha/yr	2380	19.6 Mg /ha/yr		2.2e6 m2	2.2	Asia	ND	CN element analyser	ND	1995	ND	NA	35e6 m3		120	175
Sobek et al. 2009; Sobek et al. 2012	Wohlen	46.9691	7.2851	Switzerland	0.27-2.8%	1.81	1113 ± 482 (536 to 4950)	1113	7.8 ±2.4 (5.2-11.5)	cm/yr	2.5	2.5	Europe	ND	Catalytic oxidation LECO CHNS-932	ND	1920	ND	NA		Meso to eutrophic	6816	2726

Table-SI-4-1. Database of studies with estimates of whole-reservoir carbon burial.

4.12.1 References Cited

Almeida, R.M., Nóbrega, G.N., Junger, P.C., Figueiredo, A.V., Andrada, A.S., de Moura, C.G.B., Tonetta, D., Oliveria, E.S. Jr., Araújo, F., Rust, F., Piñeiro-Guerra, Mendonça, J.R. Jr., Medeiros, L.R., Pinheiro, L., Miranda, M., Costa, M.R.A., Melo, M., Nobre, L.G., Benevides, T., Roland, F., de Klein, J., Barros, N.O., Mendonça, R., Becker, V., Huszar, V.L.M, and S. Kosten (2016). High primary production constrasts with intense carbon emission in a eutrophic tropical reservoir. Frontiers in Microbiology 7(717), http://www.doi.org/0.3389/fmicb.2016.00717

Carnero-Bravo, V., Merino-Ibarra, M., Ruiz-Fernandez, A. C., Sanchez-Cabeza, J. A., and Ghaleb, B. (2015). Sedimentary record of water column trophic conditions and sediment carbon fluxes in a tropical water reservoir (Valle de Bravo, Mexico). *Environmental Science and Pollution Research, 22(6)*, 4680-4694. https://doi.org/10.1007/s11356-014-3703-0

Downing, J. A., J. J. Cole, J. J. Middelburg, R. G. Striegl, C. M. Duarte, P. Kortelainen, Y. T. Prairie, and K. A. Laube (2008). Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century. *Global Biogeochemical Cycles, 22*, GB1018, https://doi.org/10.1029/2006GB002854

Jacinthe, P. A., Filippelli, G. M., Tedesco, L. P., and Raftis, R. (2012). Carbon storage and greenhouse gases emission from a fluvial reservoir in an agricultural landscape. *Catena, 94,* 53-63. https://doi.org/10.1016/j.catena.2011.03.012

Knoll, L.B., Vanni, M.J., Renwick, W.H., and S. Kollie (2014). Burial rates and stoichiometry of sedimentary carbon, nitrogen and phosphorus in Midwestern US reservoirs. *Freshwater Biology* (59), 2342-2353.

Kunz, M. J., Wuest, A., Wehrli, B., Landert, J., and Senn, D. B. (2011). Impact of a large tropical reservoir on riverine transport of sediment, carbon, and nutrients to downstream wetlands. *Water Resources Research, 47(12),* W12531, https://doi.org/10.1029/2011WR010996..

Kunz, M.J., Wüest, A., Wehrli, B., Landert, J., and D. B. Senn (2011). Impact of a large tropical reservoir on riverine transport of sediment, carbon, and nutrients to downstream wetlands. *Water Resources Research* (47), W12531, http://doi.org10.1029/2011WR010996

Mendonça, R., Kosten, S., Sobek, S., Cole, J. J., Bastos, A. C., Albuquerque, A. L., Cardoso, S. J., and Roland, F. (2014). Carbon Sequestration in a Large Hydroelectric Reservoir: An Integrative Seismic Approach. *Ecosystems, 17(3),* 430-441. https://doi.org/10.1007/s10021-013-9735-3

Némery, J., Gratio, N., Doan, P.T.K, Duvert, C., and R. Alvarado-Villanueva (2016). Carbon, nitrogen, phosphorus, and sediment sources and retention in a small eutrophic tropical reservoir. *Aquatic Sciences* (78), 171-189.

Pittman, B., Jones, J. R., Millspaugh, J. J., Kremer, R. J., and Downing, J. A. (2013). Sediment organic carbon distribution in 4 small northern Missouri impoundments: implications for sampling and carbon sequestration. *Inland Waters, 3(1)*, 39-46. https://doi.org/10.5268/IW-3.1.507

Pondell, C.R. and Canuel, E.A. (2017). The role of hydrodynamic sorting on the accumulation and distribution of organic carbon in an impoundment: Englebright Lake, California, USA: *Biogeochemistry, 133(2)*, 129-145. https://doi.org/10.1007/s10533-017-0319-8

Sobek S., Durisch-Kaiser E., Zurbrugg R., Wongfun N., Wessels M., Pasche N., and Wehrli, B. (2009). Organic carbon burial efficiency in lake sediments controlled by oxygen exposure time and sediment source. *Limnology and Oceanography*, 54 2243–2254, https://doi.org/10.4319/lo.2009.54.6.2243

Sobek, S., DelSontro, T., Wongfun, N., and Wehrli, B. (2012). Extreme organic carbon burial fuels intense methane bubbling in a temperate reservoir. *Geophysical Research Letters, 39 (L01401)*, https://doi.org/10.1029/2011GL050144

Thothong, W., Huon, S., Janeau, J., Boonsaner, A., de Rouw, A., Planchon, O., Bardoux, G., and Parkpian, P. (2011). Impact of land use change and rainfall on sediment and carbon accumulation in a water reservoir of North Thailand, *Agriculture, Ecosystems and Environment*, 140, 521-533. https://doi.org/10.1016/j.agee.2011.02.006

Vanni, M. J., Renwick, W. H., Bowling, A. M., Horgan, M. J., and Christian, A. D. (2011). Nutrient stoichiometry of linked catchment-lake systems along a gradient of land use. *Freshwater Biology, 56(5)*, 791-811. https://doi.org/10.1111/j.1365-2427.2010.02436.x

Zhao, L., Ji-Ming, M., Shuang-Ling, Z., Chun-Zi, N. and N. Lin-Mei (2016). Different hydrodynamic conditions on the deposition of organic carbon in sediment of two reservoirs. *Hydrobiologia* (765), 15-26.

5 Conclusions and synthesis

This study investigated the interplay between sedimentation and carbon burial in the recently removed Lakes Mills and Aldwell on the Elwha River on the Olympic Peninsula of Washington State, using the insight gained from the detailed stratigraphic models and process-based insight gained to develop a conceptual model of carbon storage in reservoirs globally and provide an intellectual foundation with which to develop future investigations.

The removal of Glines Canyon and Elwha Dams, the largest dam removal projects yet undertaken globally, presented an ephemeral first opportunity to examine the composition and architecture of reservoir sediments through direct, spatially comprehensive observation, providing a window into the structure of reservoir sediments, the processes involved, and the evolution of sedimentation styles over the lifetime of a reservoir. Within the spectrum of reservoirs occurring globally, former Lake Mills probably represents the simplest end member of reservoir sedimentation. Given its relatively simple perimeter, long, narrow morphology, pristine watershed, and operational history as predominantly run-of-the-river, former Lake Mills was similar to a deep-water, glacier-carved lake, making it interpretable in the context of the classic Gilbert delta paradigm. Given the relative simplicity of this depositional model and the accompanying excellent hydrograph record on the Elwha River, former Lake Mills provides an opportunity to assess our understanding of the dynamics of natural Gilbert-style systems and the basin-wide correlation of facies. The use of marker beds for stratigraphic correlation across systems is common in investigations of marine and lacustrine environments both ancient and modern. However, the lateral and longitudinal variability in the reservoir sediments of former Lake Mills, as well as the stochastic nature of delta slope failure, and variety of endo- and exogenic influences on sediment transport suggest that correlation of individual flow events in systems this dynamic may be quite speculative.

In contrast to former Lake Mills, the sediments of former Lake Aldwell were characterized by complex facies architecture influenced by the 1) the major reduction in total sediment load following the upstream closure of Glines Canyon Dam, 2) the relative fining of the remaining sediment load due to differences in the rate of bedload vs.

suspended load capture by the dam, and 3), the influx of a significant landslide-runout to the upper delta plain. The stratigraphic exposures examined suggest that former Lake Aldwell was characterized by a high-volume, bedload-dominated Gilbert-style delta prior to the upstream closure of Glines Canyon Dam in 1927, after which it was overprinted with the characteristics of a fine-grained, sediment-starved system dominated by mouth-bar, shoal-water style sedimentation. While some of the drivers influencing former Lake Aldwell are inevitably case-specific, the resulting delta represents a system not found in natural systems: that of a steep-profiled but fine-grained system. Existing frameworks developed for lacustrine systems do not describe these systems well, suggesting that robust characterization of reservoir sedimentation in many systems requires the development of new conceptual frameworks.

Building on the stratigraphic interpretations made in Chapter 2, the analysis of organic matter deposition and carbon storage in the sediments of former Lakes Mills and Aldwell illustrates the complexity of reservoir sedimentation dynamics and carbon burial therein. The volume of coarse-grained organic matter deposition in both reservoirs indicates that reservoir deltas are important sites of carbon storage and that the failure to account for heterogeneity of sediment deposition in reservoir basins may result in error in burial estimates of nearly 50%. While much of the coarse-grained organic matter deposition is concentrated in deltaic regions, differences between former Lakes Mills and Aldwell illustrate the importance of understanding reservoir-specific depositional processes when designing studies to investigate the dynamics of carbon burial and reservoir sedimentation. Methods which fail to account for the accumulation of coarse woody debris, the importance of event-based deposition, or the three-dimensional variability in sediment architecture will produce overly simplistic conceptual models of sedimentation and are likely to result in significant error in total carbon storage estimates.

In environments beyond the mountainous, temperate environment of the Elwha River watershed, reservoir sedimentation may be further characterized as dominated by turbidity currents funneled along the thalweg of the former reservoir or (typically in small reservoirs) as dominated by suspended sediment deposition in a lacustrine, homogeneous environment. However, the conceptual models of reservoir sedimentation and carbon burial discussed above suggest that many of the assumptions inherent in most estimates of carbon burial in reservoirs, including the implicit assumption that coarse grained organic matter may be "conspicuous" but tends to be insignificant in the total carbon load in fluvial environments, and the homogenizing influence of sediment resuspension and deposition in the reservoir "depocenter", and the assumption that long, narrow reservoirs can be reasonably approximated using a few limited samples collected along a longitudinal transect of the reservoir and excluding input from tributaries, do not hold up in most reservoir environments.

Without a process-based understanding of the primary depositional processes operating in a given reservoir and their evolution through time, estimates of carbon burial in reservoir sediments are inconclusive. Over the lifespan of a given reservoir, dominant sediment-delivery processes may evolve in response to morphological changes, watershed influences, or changes in operation, which in turn influence the deposition and burial of organic matter. However, while the individual dynamics of Gilbert style, shoalwater, thalweg, and lacustrine-style reservoirs vary, the longitudinally-oriented sampling designs most common to studies of reservoir and carbon sedimentation appear to be biased to fine-grained sediments, probably resulting in the significant underestimation of organic matter preservation in reservoirs globally. To reduce the uncertainty in estimates from these dynamic environments, we suggest that investigations into carbon burial should be rooted in a stratigraphic or process-based context that ensures the representation of the full range of sediment and detrital organic conditions across the reservoir.

As a result, we suggest that the net balance between greenhouse gas production and surface emission and carbon burial remains poorly constrained. This uncertainty reveals gaps in our fundamental understanding of depositional processes and complexity of the biogeochemical environments created by reservoirs and suggests the need for greater investigation into the processes influencing fluviolacustrine environments, their evolution through time, and their responses to significant exogenic events such as drought, flood, or changes in upstream sediment regimes. Given that an increasing number of dams which have outlived their useful lifespans are now slated for removal, the scientific community stands on the precipice of a unique opportunity to investigate these dynamics. By using these modern, relatively controlled environments to better understanding the influential processes governing sedimentation and carbon deposition in fluviolacustrine environments we can develop better understandings of lacustrine environments both modern and ancient.