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Sediment and phosphorus dynamics within the channel and floodplain of Walnut Creek, Iowa

by

William J. Beck

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Environmental Science

Program of Study Committee:
Thomas M. Isenhart, Major Professor
John L. Kovar
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Keith E. Schilling
Richard C. Schultz

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2018

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DEDICATION

This work is dedicated to Jenny Beck. Thank you for allowing me to put our lives on hold the past four years so I could pursue this.
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Excessive loadings of sediment and phosphorus (P) to waterways are prime water quality impairments within both the agricultural Midwestern United States of America (USA) and globally. Streambanks, floodplains, and channel beds may all significantly influence watershed export of suspended sediment (SS) and total phosphorus (TP), yet mechanisms at the watershed scale are poorly understood. This study seeks to investigate the dynamic influences of streambank erosion, channel-floodplain connectivity, and in-channel storage on SS and TP export within Walnut Creek, a third-order, alluvial stream channel in central Iowa, USA. Channel cross-sectional change data suggest that Walnut Creek is currently experiencing degradation and widening (stage IV of channel evolution) in response to historic land use and hydrologic alterations. Over study duration, Walnut Creek’s streambanks were estimated to contribute the equivalent of 4.0 to 43.9% of previously reported annual watershed SS loads, and the equivalent of 2.7 to 37.5% of TP loads. It was estimated that colluvial material, generated from streambank mass wasting and subaerial weathering and erosion processes, dominated bank SS and TP contributions to loads. An increase in channel cross-sectional area of ~17% over 16 years has reduced the lateral connectivity between Walnut Creek and its floodplain. Overbank discharge threshold (i.e., discharge required to force streamflow to exit channel and inundate floodplain) increased 15% over the same time period, resulting in decreases in annual suspended sediment (~24%) and TP (~26%) fluxes to floodplain storage. Walnut Creek was estimated to store sediment at the rate of ~2.7 Mg per m channel length, and TP at the rate of 0.7 Mg per m channel length. Sinuous reaches (sinuosity > 1.2) stored a significantly greater (p < 0.001) volume of sediment than straight reaches, and also
exhibited significantly greater (p < 0.001) sediment depth. In-channel storage may be a significant component of watershed sediment and TP budgets. Total in-channel sediment storage was estimated at 36,554 Mg, ~3.25 times greater than the 2015 watershed SS load. Rehabilitation strategies that decrease channel conveyance and velocities (e.g., introduced meandering) may increase streambank stability, restore channel-floodplain connectivity, and reduce watershed export of SS and TP.
CHAPTER 1. INTRODUCTION

Excessive loadings of sediment and phosphorus (P) to waterways are prime water quality impairments within both the agricultural Midwestern United States of America (USA) and globally (USEPA, 2018). Excessive sedimentation negatively impacts aquatic habitat, reduces drinking water reservoir storage capacity, increases drinking water treatment costs, and diminishes waterbody-associated economic and recreational opportunities. Phosphorus is often the limiting nutrient for algal primary production in freshwater systems (Daniel et al., 1998; Smith, 2003), and excess loading may contribute to accelerated eutrophication, harmful algal blooms (HABs), and coastal hypoxic zones.

A growing body of literature suggests that in-channel sources represent a significant, albeit highly variable, source of both suspended sediment (SS) and P to stream loads (Fox et al., 2016). The magnitude and partitioning of in-channel sources may be influenced by changes in channel conveyance brought about by large scale disturbances to land cover (e.g., row crop conversion) or hydrology (e.g., stream straightening). In alluvial channels, such as Walnut Creek, response to disturbance occurs through a relatively consistent pattern of adjustments collectively known as the channel evolution model (CEM) (Schumm et al., 1984; Simon, 1989). The initial response is for the channel to incise (referred to as stage III), followed by subsequent stages of degradation and widening (IV), and aggradation and widening (Stage V) before returning to relative stability (stage VI).

A number of studies in Walnut Creek (Schilling and Wolter, 2000; Palmer et al., 2014; Beck et al., 2018) have documented conditions (e.g., channel instability, streambank erosion) that suggest the channel is exhibiting a pattern of disturbance-driven
adjustments consistent with the CEM. The implications of these adjustments for watershed SS and TP loading will be the primary focus of this paper.

In Walnut Creek, recent work by Gellis et al. (2017) suggests that in-channel material (e.g., streambanks) is the primary source of watershed suspended sediment. Research by Palmer et al. (2014) also suggests streambanks as a significant source of Walnut Creek annual suspended sediment loads, however, high variability in annual contributions exists (0-53%). Global studies have documented similar ranges, with streambanks contributing between 18 and 89% (Bull, 1997; Kronvang et al., 1997; Russell et al., 2001; Walling and Woodward, 1995) of annual suspended sediment loads. Significant, yet highly variable, streambank contributions have also been documented for total phosphorus (TP) annual loads (Miller et al., 2014; Sekely et al., 2002; Thoma et al., 2005) within the USA and globally (Kronvang et al., 1997; Walling et al., 2008). However, studies quantifying streambank SS and TP loading remain limited in both number and regional representation (Fox et al., 2016). Because of the relative paucity and high variability of data, streambank SS and TP loading is commonly absent from local and regional water quality strategies aimed at reducing nutrient loading, such as the Iowa Nutrient Reduction Strategy (INRS) (IDALS et al., 2014).

Streambank material characteristics (e.g., bulk density, structure, texture) exhibit a high degree of variation at the individual-bank and watershed scales (Daly et al., 2015; Kessler et al., 2013; Konsoer et al., 2016; Parker et al., 2008), and banks in alluvial streams may be comprised of numerous, distinct, stratigraphic alluvial units (Layzell and Mandel, 2014; Schilling et al., 2009). Material variation among units, along with stratigraphic position, may have significant implications for sediment and P loading, as units may be
impacted differently, both spatially and temporally, by specific erosional processes (Hooke, 1979; Wolman, 1959). Inherent unit material characteristics (e.g., equilibrium P concentration, degree of P saturation) may influence in-channel P dynamics (e.g., adsorption, desorption) following erosion (Hongthanat et al., 2011). Despite the importance of such differences in individual bank materials, the vast majority of studies that aim to quantify streambank sediment and P loading focus solely on whole-bank contributions. In addition, a dearth of studies currently exist which investigate load contributions from the distinct alluvial units that comprise banks.

Connectivity between a stream channel and its floodplain through lateral overbank flow represents a vital pathway for the transfer and exchange of energy and materials between aquatic and terrestrial ecosystems (Tockner et al., 1999; Bayley, 2014). A service of particular importance is the ability of floodplains to trap and store sediment and nutrients delivered with inundating overbank flow (Venterink et al., 2003; Noe and Hupp, 2009; Hopkins et al., 2018). Floodplain storage has been documented as a significant component of watershed sediment budgets (Walling et al., 1998), especially in systems experiencing aggradation in response to disturbance (Trimble, 1983). Disconnect between the channel and floodplain frequently occurs when changes in channel geometry increase channel conveyance, similar to the disturbance-driven adjustments described in the CEM. If floodplain inundation frequency and extent decrease as a channel progresses through stages III-V, a significant reduction in floodplain storage of suspended sediment (SS) and total phosphorus (TP) may occur. This reduction in floodplain storage is of importance, as it may lead to increases in watershed-scale SS and TP export. Although the progression of a channel through the CEM may have important implications on SS and TP budgets, few
studies currently take disturbance-driven channel adjustment into account when addressing SS and TP export at the watershed scale.

Sediment storage within stream channels has been recognized as a significant component of watershed sediment budgets (Lambert and Walling, 1988), a potentially large contributor to watershed suspended sediment loads (Collins and Walling, 2007; Walling et al., 1998), and may act as a control on sediment routing within watersheds (Walling and Amos, 1999; Smith and Dragovich, 2008). Especially important in the Midwestern U.S. is the association of sediment with phosphorus (P) (Sharpley et al., 2013). In-channel sediment storage has potential to act as a significant source or sink of P to streamflow through processes such as adsorption / desorption, and these processes may vary considerably depending on stream physiochemical conditions and inherent properties of stored sediment (Hongthanat et al., 2016; Rahutomo et al., 2018).

Quantification of in-channel sediment presents a series of challenges, notably the exceptionally high spatial and temporal variability of stored material (Heitmuller and Hudson, 2009; Walling et al., 2002), and the laborious, extensive field sampling needed to address this variability (Lambert and Walling, 1988). Thus, despite its importance to watershed processes, quantification of in-channel sediment and P storage at the watershed scale is rare. In addition, the majority of studies that do exist do not focus on the heavily-altered systems of the Midwestern U.S.

The overall objective of this research is to advance our understanding of in-channel and associated floodplain sediment and P dynamics within watersheds. Chapter 2, “Streambank Alluvial Unit Contributions to Suspended Sediment and Total Phosphorus Loads, Walnut Creek, Iowa, USA” seeks to quantify SS and TP loading from
four distinct Holocene materials comprising streambanks through analyses of a high
 temporal resolution, watershed-scale streambank erosion dataset. Chapter 3, “Changes in
 Lateral Floodplain Connectivity Accompanying Stream Channel Evolution: Implications
 for Sediment and Nutrient Budgets” utilizes a combination of in-field channel cross
 section measurements, hydraulic modeling, and stream gauging station-derived water
 quality and quantity data to investigate changes in floodplain inundation and storage over
 a 16 year period in the context of the CEM. Chapter 4, “Sediment Storage within an
 Alluvial Stream Channel, Iowa, USA”, seeks to quantify and characterize in-channel
 sediment storage within 13.5 km of Walnut Creek’s main stem, and allocate storage
 based on depositional processes and location within the channel. It is intended that this
 research help inform state and regional nutrient reduction strategies and policy aimed at
 enhancing water resources, assist in prioritizing watershed rehabilitation efforts on-the-
ground conservation funding and rehabilitation efforts, and help reduce the knowledge
 gap regarding in-channel and floodplain sediment and P dynamics.

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CHAPTER 2. STREAMBANK ALLUVIAL UNIT CONTRIBUTIONS TO SUSPENDED SEDIMENT AND TOTAL PHOSPHORUS LOADS, WALNUT CREEK, IOWA, USA

A manuscript published in Water

William Beck, Thomas Isenhart, Peter Moore, Keith Schilling, Richard Schultz, and Mark Tomer

Abstract

Streambank erosion may represent a significant source of sediment and P to overall watershed loads, however, watershed-scale quantification of contributions are rare. In addition, streambanks are often comprised of highly-variable stratigraphic source materials (e.g., alluvial deposits), which may differentially impact in-channel P-dynamics once eroded. The objective of this study was to quantify sediment and TP losses from four materials comprising streambanks within a 5218 ha watershed in Iowa, USA. Streambank-face surveys, erosion pins, and soil analyses were used to quantify surface area representation, recession, and losses of sediment and total phosphorus (TP) over a two year period. Cumulative, whole-bank gross mean recession totaled 18.6 cm over two years, and material-specific gross mean recession ranged from 15.5 to 64.1 cm. Cumulative, whole-bank mean gross mass losses totaled 0.28 Mg sediment and $0.7 \times 10^{-5}$ Mg TP per meter channel length. Annual sediment losses equated to 4-44% of historic suspended sediment loads. Stratigraphy was significant in gross material erosion and losses, with lower materials (i.e., bank toe region) exhibiting the greatest recession rates and cumulative recession. Weathered/colluvial material dominated total bank face surface area (88.3%), and contributed the greatest proportion of sediment and TP mass loss (66, 68%, respectively) versus other streambank materials.
2.1 Introduction

Excessive loadings of sediment and phosphorus (P) to waterways are prime water quality impairments within both the agricultural Midwestern United States of America (USA) and globally [1,2]. Excessive sedimentation negatively impacts aquatic habitat, reduces drinking water reservoir storage capacity, increases drinking water treatment costs, and diminishes waterbody-associated economic and recreational opportunities. Phosphorus is often the limiting nutrient for algal primary production in freshwater systems [3], and excess loading may contribute to accelerated eutrophication, harmful algal blooms (HABs), and coastal hypoxic zones.

A growing body of literature suggests that streambank erosion often represents a significant, albeit highly variable, source of both suspended sediment (SS) and P to stream loads [4]. In the Midwestern and southern USA, studies have documented a wide range of streambank contributions to annual SS loads, with contributions ranging from 25-60% [5–9], up to 80-96% [10–12]. In Walnut Creek, recent work by Gellis et al. [13] suggests that in-channel material is the primary source of watershed suspended sediment. Research by Palmer et al. [14] also suggests streambanks as a significant source of Walnut Creek annual suspended sediment loads, however, high variability in annual contributions exists (0-53%). Global studies have documented similar ranges, with streambanks contributing between <19% [15–17], and up to 89% [18] of annual suspended sediment loads. Significant, yet highly variable, streambank contributions have also been documented for total phosphorus (TP) annual loads [8,19,20] within the USA and globally [18,21]. However, studies quantifying streambank SS and TP loading remain limited in both number and regional representation [4]. Because of the relative paucity and high variability of data, streambank SS and TP loading is commonly absent.
from local and regional water quality strategies aimed at reducing nutrient loading, such as the Iowa Nutrient Reduction Strategy (INRS) [22].

Streambank material characteristics (e.g., bulk density, structure, texture) exhibit a high degree of variation at the individual-bank and watershed scales [23–26], and banks in alluvial streams may be comprised of numerous, distinct, stratigraphic alluvial units [27,28]. Material variation among units, along with stratigraphic position, may have significant implications for sediment and P loading, as units may be impacted differently, both spatially and temporally, by specific erosional processes [29,30]. Inherent unit material characteristics (e.g., equilibrium P concentration, degree of P saturation) may influence in-channel P dynamics (e.g., adsorption, desorption) following erosion [31]. Despite the importance of such differences in individual bank materials, the vast majority of studies that aim to quantify streambank sediment and P loading focus solely on whole-bank contributions. Very few studies to date have investigated load contributions from the distinct alluvial units that comprise banks, with many of these focusing on post-European settlement alluvium [32–35]. For many erosional studies, points of measurement have not been stratified by alluvial unit, but rather by general bank region (e.g., upper, mid, lower bank) [36,37]. In addition, the objectives of these studies have been to elucidate erosional processes spatially and temporally [34,38], and not to quantify annual load contributions.

The overall objective of this study was to quantify sediment and TP loading over a two year period from four distinct Holocene materials comprising streambanks in Walnut Creek, Iowa, USA. Specific objectives were to assess alluvial unit differences in (i) surface area representation on eroding streambank surfaces, (ii) lateral recession, (iii) sediment mass contribution at the watershed scale, (iv) TP mass contribution at the watershed scale, and (v)
erosional response to stream discharge. This study provides a unique, high temporal resolution dataset of alluvial unit-specific erosion and potential contribution to SS and TP loads at the watershed scale. Datasets such as this are valuable for increasing the regional representation of streambank loading studies, informing Total Maximum Daily Loads (TMDLs) and state and basin-wide nutrient reduction strategies, as well as augmenting modeling efforts intent on predicting long term in-channel P dynamics.

2.2 Materials and Methods

2.2.1 Watershed Description

Walnut Creek is a perennial, third order stream draining 5218 ha in Jasper County, Iowa (Figure 2.1). The Walnut Creek watershed is located in the Rolling Loess Prairies Level IV Ecoregion (47f), a region typified by rolling topography and well-developed drainage systems [39]. The ecoregion is a subdivision of the Western Corn Belt Plains Level III Ecoregion (47), which is characterized as having 75% of the land area used for cropland agriculture, and a significant portion of the remaining landscape used for livestock grazing and forage. Walnut Creek is located within a humid, continental region with average annual precipitation of approximately 750 mm. The months of May and June generally exhibit the highest monthly precipitation totals, however, large convective thunderstorms can occur during the summer months and may produce rapid increases in stream discharge.

Watershed land use consists of 54% row crop agriculture (primarily corn-soybean rotation), 36% grassland, and 4% forest, with the remainder comprising roads, farmsteads, and urban areas [40]. Of the grassland area, 25.4% is recently restored tallgrass prairie established by the U.S. Fish and Wildlife Service (USFWS) as part of the Neal Smith National Wildlife Refuge (NSNWR). Since refuge creation in 1991, large tracts of row crop agricultural land have been converted to native tallgrass prairie and savanna. The riparian area of the
watershed’s upper reaches is dominated by single-species stands of reed canary grass (RCG) (*Phalaris arundinacea*), while interspersed RCG-riparian forest is typical of the watershed’s lower reaches.

Watershed soils are primarily silty clay loams, or clays formed in loess or till. The upland surficial geology is comprised of a 1-6 m loess cap overlaying pre-Illinoian glacial till, with Holocene alluvial deposits being comprised primarily of silty clay loams, clay loams, or silt loams [27]. A majority of watershed soils exhibit moderate to high erosion potential, with 54% being classified as highly erodible [41].

Walnut Creek is incised more than 3 m into its floodplain, and is typified by tall, cohesive streambanks. The effects of historic agricultural-associated practices such as row crop conversion, stream straightening, subsurface drainage, and removal of riparian vegetation [42,43], have led to a flashy hydrology, with Walnut Creek frequently exhibiting rapid responses to precipitation. Mean daily stream discharge at the watershed outlet ranged from a high of 11.28 to a low of 0.09 m$^3$ sec$^{-1}$ over the study duration. Several stages of stream channel evolution have been documented through ~20 years of channel cross sectional measurements initiated by Schilling and Wolter [42], with areas of Stage III (degradation), Stage IV (degradation and widening), and Stage V (aggradation and widening) present [44]. Field observations indicate Stage IV as the most prevalent along Walnut Creek’s main stem.

### 2.2.2 Streambank Alluvial Units

Walnut Creek’s floodplain is comprised of a series of loess-derived Holocene alluvial deposits, collectively known as the DeForest Formation [45]. The formation is divided into members based on lithologic properties (e.g., color, texture, pedogenic alterations). Three primary members of the DeForest Formation comprise Walnut’s streambanks (Figures 2.2).
The Gunder member represents the oldest streambank material, deposited ~10,000 - 3,500 years before present (ybp) [46], and is found at depths of approximately 1-3 m [27] (Figure 2.3). The Gunder was deposited during a relatively cool and wet climatic period, typified by higher magnitude streamflow events and a deciduous forest landcover [47,48]. The high flow regime during deposition resulted in the Gunder having the coarsest texture (sand content 28.5%) of the three members [46]. The Gunder occupies the lowest stratigraphic position and, when exposed, comprises the bank toe and streambed (Figure 2.3). The Gunder has been classified as a silt loam, with massive structure, and a gleyed / reduced matrix with redoximorphic concentrations generated from past water table fluctuations [27] (Figure 2.4).

The Roberts Creek member overlies the Gunder (Figure 2.3), and is described as a silty clay loam [27] (Figure 2.4). Deposition occurred ~3,500 – 500 ybp, in the context of a tallgrass prairie-savanna dominated landscape [46,49]. The Roberts Creek represents the pre-Euro-American settlement landscape surface, and exhibits a relatively high organic matter content [27], and well defined sub-angular blocky structure. Flow regime during deposition was typified by smaller, less intense streamflows [49], which resulted in the Roberts Creek having the greatest clay content of the three members.

The Camp Creek member overlies the Roberts Creek and represents the upper stratigraphic position (i.e., floodplain surface) (Figure 2.3). Camp Creek was deposited during the last ~400 years [46], and is typically referred to as ‘post-European settlement alluvium’. Camp Creek is described as a silt loam, with fine granular structure, light color, and the highest silt content of the three members (Figure 2.4). Thickness of the Camp Creek ranges from 0.6 to 1.8 m [27]. Camp Creek is heavily stratified, with abundant striations resulting from layering during floods. Hereafter, the terms ‘alluvial unit’ and ‘member’ will be used interchangeably.
A fourth material of interest is streambank non-member material (NMM) that amasses at the toe and mid zones of streambanks (Figure 2.5). The NMM was observed as being comprised of material eroded from upper stratigraphic units (termed colluvial material), weathered but non-detached member material, and recent deposits of alluvium. Although three sources are recognized as comprising NMM, colluvial material was by far the greatest observed component. Colluvium is transported to the lower and mid bank regions gravitationally as a result of mass wasting and subaerial processes (e.g., freeze-thaw cycles). The NMM was ubiquitous in all study reaches, albeit highly variable both spatially and temporally. When present, the NMM would drape bank faces, creating a non-vertical wedge that covered all or parts of specific units (Figure 2.5). The exposed bank face thickness of Camp Creek, Roberts Creek and Gunder units generally depends on stream reach incision, and the prevalence of NMM.

Distribution, stratigraphic position, thickness, and inherent soil characteristics (e.g., texture, bulk density) of the Camp Creek, Roberts Creek, and Gunder members have been documented as being consistent throughout the watershed [27]. The alluvial stratigraphy in the watershed is typical of many other loess-mantled areas of the Midwestern USA [45].

2.2.3 Eroding Streambank Length Survey and Streambank Plot Selection

In November 2013, an on-the-ground streambank erosion survey was conducted along 13.5 km of the main stem of Walnut Creek. Banks identified as exhibiting severe or very severe erosion based on Natural Resources Conservation Service (NRCS) protocol [50] were georeferenced. Length and average bank height were recorded for all identified banks using meter tape and survey rods. Upon completion of the assessment, banks were randomly selected until a length equivalent to 20% of total main stem eroding length was reached. This set of banks was to become an overall set for a related, large-scale study, and comprised 61
total streambanks. A subset of banks equivalent to 20% of the 61-bank set length was also randomly selected. This subset comprised 10 banks, which ranged in length from 16 to 108 m. The 10 bank subset was designated for fine temporal scale streambank erosion quantification, as well as member-specific erosion quantification, and is the focus of this paper. The eroding length survey was repeated in April, 2016 and March, 2017. It should be noted, however, that the additional surveys were intended to quantify total eroding length for watershed-scale erosion extrapolation purposes, and not to select new sets of streambanks for this study.

2.2.4 Streambank Plot Design and Measurement Protocol

Streambank erosion pins [30] were used to quantify streambank recession. Pins were made of steel, with dimensions of 762 mm length and 6.2 mm diameter. Pins of these dimensions were utilized based on successful use during previous Walnut Creek [14] and Iowa [51,52] streambank erosion studies. The pin method was selected based on the practically for measurement of small changes in bank surfaces that may be subjected to erosion or deposition [53]. Pins were installed in a rectangular, column-row grid pattern, with columns spaced at 2 m horizontal intervals. Vertical row spacing was based on stratigraphic alluvial units (i.e., Camp Creek, Roberts Creek, Gunder), with pins being installed at the vertical midpoint of exposed units. Within NMM-draped alluvial units, pins were installed at the estimated unit midpoint based on adjacent areas of exposure. Pins were inserted perpendicular to the streambank face, with a 9 cm section left exposed. During measurement periods, the exposed length of each pin was recorded using a three-sided engineering ruler, with a positive change from previous measurement (i.e., increase in exposed length) indicating bank recession, and a negative change (i.e., decrease in exposed length) indicating deposition. If measured exposed length exceeded 9 cm, pins were reset to the original measurement of 9 cm following
measurement. Resetting occurred on all >9 cm exposure pins unless researchers believed the act of resetting would cause excessive soil disturbance (e.g., extremely dry, brittle bank face conditions). Lost pins were recorded as having a recession of 600 mm based on previous studies [29,51] and personal observations of that threshold being the point where pins could maintain position under their own weight. Buried pins were located using a metal detector, and deposition was recorded as previous length of exposure. Both lost and buried pins were recorded as such, and replaced in their respective locations.

Member-specific pin measurements occurred on an approximate monthly basis beginning in May, 2015 and continued until April, 2017. In addition, measurements were performed immediately following flow events where peak discharge at the watershed outlet exceeded 8.5 m³ s⁻¹, which represents an approximate 1.5 m increase in stream stage. The interval between measurement periods were extended during times of ice cover and other scenarios that would inhibit accurate pin measurement. A total of 21 individual measurement periods were recorded for the 10 bank subset.

During individual pin measurements, the alluvial unit present at the pin-bank surface interface was recorded. This allowed for future linking of recession rate with individual unit. Consistency was adhered to when identifying units in the field, with identification based heavily on descriptions by Bettis [45]. The NMM was identified as being in a state other than that described by Bettis [45]. Common justifications for assigning NMM included evidence of recent downward movement as well as significant deviation from described member color, texture, and bulk density (i.e., indicative of material detachment and mixing).

2.2.5 Streambank Soil Sample Extraction and Analyses

Soil samples were extracted from each streambank in the 10 bank subset and analyzed for bulk density, particle size, wet aggregate stability, and total phosphorus (TP). At each bank,
one bulk density and one bulk soil sample were collected from all exposed units. Bulk density samples were extracted using a 7.62 cm x 7.62 cm open-ended bulk density cylinder. Bulk soil was used for particle size, wet aggregate stability, and TP analyses. Bulk density was determined by drying core samples at 105°C for 24 h to determine dry weight. Dry weight of samples was then divided by core volume to calculate bulk density. Wet aggregate stability was determined by machine sieving, and particle size analysis was performed using the pipette method [54]. Samples were analyzed for TP using the aqua regia method [55]. Readings from individual banks were averaged to produce a watershed-mean estimate for each unit.

2.2.6 Quantification of Streambank Alluvial Unit Surface Area

Exposed streambank face surface area of alluvial units was measured annually each August using bank-face grid surveys. During surveys, a survey rod was extended from bank toe to top bank lip along each vertical pin column. Bank angle, height, and member depth were recorded for each column. For each individual bank, column data were compiled to calculate the total surface area representation (%) of respective units. For each unit, all individual bank surface area percentages were averaged to produce a watershed-mean surface area percent (i.e., percent total eroding streambank surface area represented by each unit). Data from the August 2015 survey were applied to May 2015 – April 2016 pin recession data, while data from the August 2016 survey were applied to May 2016 – April 2017 pin recession data.

2.2.7 Quantification of Sediment and TP Mass Contribution

2.2.7.1 Calculation of mass contribution

For each measurement period, unit-specific sediment mass contribution was calculated using the product of watershed-mean unit recession (m), total watershed unit surface area (m²), and watershed-mean unit bulk density (kg m⁻³) (Equation 2.1). Mean unit recession was
calculated by averaging individual unit-specific pin readings. Total watershed unit surface area was calculated by multiplying the average unit representation (percent total bank surface area) from all banks by the total streambank surface area calculated during respective eroding length surveys. This allowed for extrapolation of individual bank measurements to the watershed scale. Eroding length totals from the 2016 survey were applied to May 2015 – April 2016 pin measurement periods (hereafter referred to as Year 1), and those from the 2017 survey were applied to May 2016 – April 2017 pin measurement periods (hereafter referred to as Year 2).

Unit-specific TP mass contribution per bank was calculated using the product of bank sediment mass contribution (kg) and watershed-mean TP concentration (kg m$^{-3}$) (Equation 2.2). Period sediment and TP masses were summed to produce cumulative mass contributions for the study duration. Unit recession rates were calculated by dividing mean period recession by time (days) between sampling periods.

### 2.2.7.2 Assigning units to individual pin readings

Because of the dynamic nature of streambank erosion, individual pins often alternated between NMM and a specific unit in subsequent measurements. In order to properly assign a pin recession reading to either NMM or the respective unit, assumptions were adhered to based on in-field observations of bank material erosion and the flashiness of Walnut Creek’s hydrology. As a result, three scenarios existed where NMM could have been assigned to an individual pin during a measurement period (Table 2.1): 1.) NMM was present at the bank-pin interface for both the previous and current measurement dates, 2.) NMM was present at the bank-pin interface during the previous measurement date, but unit material present during current measurement date, and 3.) unit material present during previous measurement date, but NMM present during current measurement date. These scenarios assume 1.) change within NMM, 2.) erosion of NMM to expose units, and 3.) deposition of NMM to cover units,
respectively. Scenario 4 entailed unit presence at the bank-pin interface on both previous and current measurement dates. Scenario 4 assumes lateral recession of unit material. Observations of streambank NMM dynamics, Walnut Creek’s flashy hydrology, as well the hypothesis that NMM material has greater potential to be eroded (e.g., lower bulk density), supports that rapid bursts of flow would primarily affect the NMM draped over members.

When analyzing pin data, NMM was split into two categories. The category NMM Net contained all NMM pin readings, both recession (i.e., positive change pin readings) and accretion (i.e., negative change pin readings). The NMM Net category was utilized in all analyses to represent the dynamic nature of streambanks (i.e., alternating recession and accretion). The category NMM Gross contained only those NMM pins that exhibited recession. The NMM Gross category was utilized in recession and flow correlation analyses only, as a means to directly compare positive lateral erosion values with those of the alluvial units. A final category, Total Bank, was calculated as a means to compare recession, as well as sediment and TP mass losses, with similar studies that relied on whole-bank estimates (i.e., no unit categories) of erosion. Total Bank was calculated by averaging all pin readings for each measurement period, without placing pins into material categories.

2.2.7.3 Negative pin readings

Negative pin readings (i.e., reduction in exposed pin length) were observed for all units and NMM during the study. Negative readings present a challenge, and decisions on when and how to include negative pin readings in calculations should be based on study objectives [56]. For this study, negative pin readings were included in calculations related to NMM-assigned pin readings, as we wanted to document both recession and deposition of this material. All negative readings for actual units, however, were changed to 0 cm prior to recession calculations. The reasoning behind this was twofold. First, researchers were consistent in
identification of unit vs. NMM in the field. Thus, the identification of bank material as a unit would preclude the deposition / presence of NMM. Secondly, if presence of NMM was precluded, likely causes of a negative reading could have been bank soil shrink/swell, and/or human measurement error [56]. Because our study objective was to quantify contributions of bank material to stream loads, there was essentially no difference (utility-wise) between a negative unit reading and a 0 cm reading. Pin studies involve inherent measurement error and assumptions [53], and it should be noted that the vast majority of negative unit readings were <1 cm of change, which is not unreasonable to attribute to human measurement error.

2.2.8 Correlation with Discharge

For each pin sampling period, watershed-outlet total discharge (m$^3$) and maximum daily mean discharge (m$^3$ sec$^{-1}$) were individually correlated with mean pin recession and mean pin recession rate. Correlation was investigated for alluvial units, as well as NMM Net, NMM Gross, and Total Bank categories.

2.3 Results

2.3.1 Precipitation, Hydrology, and Streambank Eroding Length

Pin measurement spanned May 2015 to April 2017. The duration was divided into two periods with approximately equal number of days (Table 2.1). The period of May 2015 to April 2016 will be referred to as Year 1, while the period of May 2016 – April 2017 will be referred to as Year 2. Due to specific dates of pin measurement, the lengths of both periods varied slightly, with Year 1 spanning 358 days and Year 2 spanning 371 days.

Precipitation in Year 1 (1118 mm) was higher than Year 2 (977 mm) (Table 2.2). Average stream discharge was also higher in Year 1, with an annual mean daily discharge at watershed outlet of 0.71 m$^3$ sec$^{-1}$, versus 0.43 m$^3$ sec$^{-1}$ for Year 2 (Table 2.2). Maximum daily
mean discharge varied as well, with a maximum of 11.28 m$^3$ sec$^{-1}$ recorded in Year 1 versus a maximum of 5.43 m$^3$ sec$^{-1}$ recorded in Year 2.

2.3.2 Alluvial Unit Total Phosphorus Concentration and Soil Parameters

Alluvial unit TP concentrations ranged from 170.8 (Camp Creek) to 304.2 mg kg$^{-1}$ (Gunder) (Table 2.2). The Camp Creek and Roberts Creek units had the highest silt-clay content by weight, at 94.0 and 91.2%, respectively, with the Gunder unit the lowest (71.5). Gunder represented the greatest bulk density (1.6 g cm$^{-3}$), followed by Camp Creek (1.3 g cm$^{-3}$), Roberts Creek (1.27 g cm$^{-3}$), and NMM (1.2 g cm$^{-3}$). Roberts Creek represented the greatest percentage by weight for both large macro-aggregates (>2mm) and macro-aggregates (>0.25mm) at 11.3 and 44.9%, respectively. Gunder represented the lowest percentage by weight for both large macro-aggregates and macro-aggregates at 3.8 and 15.5%, respectively.

2.3.3 Alluvial Unit Surface Area Representation within Eroding Streambank Faces

For both Year 1 and Year 2, significant differences in surface area percent were detected among units (p-value = 0.1) (Table 2.4). For both Year 1 and Year 2, NMM dominated streambank surface area, and was greater than the combined surface area of Camp Creek, Roberts Creek, and Gunder. Although no significant difference was detected for individual units between years (p-value = 0.05), Camp Creek, Roberts Creek, Gunder and NMM all exhibited a trend in decreased surface area percent from Year 1 to Year 2.

2.3.4 Streambank Recession

2.3.4.1 Daily erosion rate

No significant difference (p-value < 0.05) in mean daily erosion rate was detected between Roberts Creek (0.89 mm day$^{-1}$), Gunder (0.99 mm day$^{-1}$), and NMM Gross (0.74 mm day$^{-1}$) (Figure 2.7). The Camp Creek mean recession rate (0.39 mm day$^{-1}$) was
significantly lower (p-value < 0.05) than Gunder, and NMM Gross, but not significantly different to Roberts Creek. The mean daily recession rate of NMM Net (0.19 mm day$^{-1}$) was found to be significantly lower than all alluvial units, as well as NMM Gross. As noted in the methodology, NMM Net was the only unit to include negative recession rates (i.e., deposition).

2.3.4.2 Cumulative recession

The Gunder and NMM Gross represented the greatest cumulative lateral recession over the study duration (64.1, 53.1 cm, respectively) (Figure 2.8). Gunder and NMM Gross were found to be significantly greater (p-value < 0.1) than Camp Creek (26.8 cm), Roberts Creek (27.3 cm), and NMM Net (15.5 cm). No significant difference was detected between Camp Creek, Roberts Creek, and NMM Net (p-value < 0.1).

Although not a primary study objective, cumulative mean recession for Total Bank (i.e., mean pin recession for individual banks, regardless of unit) was calculated for Year 1, Year 2, and study duration, for comparison to regional studies (Table 2.5). Total Bank mean cumulative recession was found to be 18.6 cm, and ranged from a minimum of 6.0 to a maximum of 42.3 cm. Year 1 exhibited a mean cumulative recession (12.3 cm) nearly double that of Year 2 (6.3 cm).

2.3.5 Streambank Sediment and TP Mass Loss

2.3.5.1 Cumulative sediment mass

Camp Creek exhibited the greatest mean cumulative sediment mass loss (598.9 Mg), followed by Gunder (528.31 Mg), and Roberts Creek (316.17 Mg) (Figure 2.9). Differences were not significant (p-value = 0.13) among the three units, however, likely due to high variability among individual-bank estimates. Although not tested statistically, a clear trend is apparent that the majority of sediment mass was lost from the Camp Creek, Roberts Creek,
and Gunder units during Year 1 (Figure 2.9). Over the study duration, combined mean sediment mass loss from the Camp Creek, Roberts Creek, and Gunder units along Walnut Creek’s main stem totaled 1443.43 Mg.

NMM Net exhibited a mean of 2488.52 Mg cumulative sediment mass loss over the study duration (Figure 2.10). This mass was 1005.09 Mg greater than the combined loss of the Camp Creek, Roberts Creek, and Gunder units. Net NMM mean cumulative sediment mass loss was found to be significant greater (p-value < 0.1) than individual contributions from the Camp Creek (p-value = 0.023), Roberts Creek (p-value = 0.063), and Gunder (p-value = 0.096) units. Total bank mean cumulative sediment mass loss totaled 3759.95 Mg along Walnut Creek’s main stem (Figure 2.10). As with the three individual alluvial units, NMM Net and total bank cumulative sediment mass losses were greatest during Year 1.

2.4 Discussion

2.4.1 Streambank Surface Area

Alluvial units and NMM were found to represent different proportions of total streambank surface area, with NMM dominating coverage (Table 2.4). Mass wasting and subaerial erosion (e.g., freeze-thaw cycling leading to soil detachment) were pervasive during the study. These processes often produce an angled accumulation of material that builds upwards from the bank toe, veiling portions of the lower and mid bank [29,44,58,59]. These processes may drive alluvial unit exposure, as lower and mid bank (i.e., Gunder, Roberts Creek) units were covered to a disproportionately greater degree than the upper bank (i.e., Camp Creek) (Table 2.4). NMM coverage could have significant impacts on unit erosion, as the NMM may act to protect units from weathering and fluvial erosion. This pattern of NMM dominance is not uncommon in streams currently classified within stage IV of channel evolution [44].
Streamflow patterns may also influence streambank unit exposure. Surface area for streambank units and NMM decreased between Year 1 and Year 2 of the study. The locations and degree of change may be partially explained by stratigraphy and streamflow. Greater total streamflow in Year 1 (Table 2.2), along with two large, near out-of-bank events may have reduced upper bank NMM, allowing for a greater Camp Creek and Roberts Creek exposure. The lower flow in Year 2 may have allowed for increased NMM accretion, primarily as colluvium from upper units, with the resulting buildup reducing Camp Creek and Roberts Creek exposure. Gunder exposure decreased from Year 1 to Year 2, however, to a lesser degree than the Camp Creek and Roberts Creek. Stratigraphy may have played a role in this, as the Gunder’s position near the bank toe subjects it to near-continuous contact with flowing water.

2.4.2 Streambank Material Recession and Streamflow Impacts

Alluvial units and NMM differed significantly in both recession rate (mm day$^{-1}$) and cumulative recession (cm). Materials spanned a wide spectrum of inherent soil properties (e.g., bulk density, texture, structure) which impact erodibility [60–62] (Table 2.3). However, in incised systems such as Walnut Creek, alluvial stratigraphy may also be a significant controlling factor.

Camp Creek exhibited both the lowest mean gross recession rate, and cumulative gross recession of all streambank materials (Figure 2.7). Compared with other streambank materials, Camp Creek has inherent soil properties that suggest low resistance to fluvial erosion, such as relatively low bulk density, high silt content, and granular structure. In addition, Layzell and Mandel [28] estimated the Camp Creek’s critical shear stress to be a relatively low 1.0 Pa, by means of an in-situ submerged jet test in northeast Kansas. However, its position at the top of Walnut Creek’s incised streambanks suggests that its contact with the stream is limited to only the largest of flow events. This assumption has been verified by in-situ time-lapse camera
footage, flood modeling (Beck et al., in prep) and has been suggested in other investigations Midwestern watersheds exhibiting channel incision [28]. In addition, given Walnut Creek’s flashy hydrology, the rare contact that Camp Creek does have with flowing water is brief in duration, which may reduce erosion potential at top-of-bank. Thus, it is likely that subaerial processes are an important erosional mechanism impacting the Camp Creek unit in Walnut Creek.

The Gunder member has inherent properties that suggest greater resistance to fluvial erosion, such as high bulk density, low silt content, and a critical shear stress of 10.4 Pa [28]. The Gunder, however, exhibited the greatest mean gross recession rate and cumulative recession of all streambank materials. Results are similar to those of Veihe et al. [38] and Laubel et al. [63] who reported highest erosion rates on lower bank regions. Again, stratigraphy may have played a significant role, as the Gunder’s position at the bank toe provides for near constant interaction with streamflow. In addition, proximity to flowing water and frequent water level fluctuations make the Gunder more susceptible to soil weakening through wetting-drying cycles [29,59] and needle ice formation [64] (field observation). The recession rate and cumulative recession of NMM Gross was slightly less than Gunder, albeit not significantly. Its inherent soil properties would suggest lower resistance to fluvial erosion (e.g., low bulk density, low clay content) (Table 2.3). It represented the majority of the bank toe and mid-bank regions of study streambanks, and thus may be subject to the same erosional processes as Gunder. The slight lower recession than Gunder may be due to presence of bank vegetation and non-vertical nature of the material (field observations).

The Roberts Creek member also has inherent properties, although different in nature than those of the Gunder, that suggest high resistance to fluvial erosion, such as high organic
matter [27], relatively high clay content, and well-defined structure (Table 2.3). However, Roberts Creek exhibited a high gross recession rate, but low cumulative gross recession among the bank materials. Its relatively high range of period recession rates (Figure 2.7), along with its low cumulative recession (Figure 2.8) may suggest that the Roberts Creek is subject to infrequent mass wasting events. Its proximity mid-bank may result in reduced contact with streamflow, as well as reduced saturation frequency from wetting fronts below and above, which would act to increase soil cohesion [61].

Most streambank units exhibited a moderate correlation between mean period recession (cm) and total pin measurement period discharge (m$^3$), as well as between mean period recession rate (mm day$^{-1}$) and maximum mean daily discharge (m$^3$ sec$^{-1}$) (Figure 13). Units present at bank toe region (i.e., Gunder, NMM Net, NMM Gross) had the greatest correlation with total period discharge. Total bank also exhibited a relatively strong correlation with total discharge. This may be expected, as NMM was found to represent 79.4 - 87.1% of total bank surface area. Among alluvial units, the correlation between recession rate and maximum discharge was strongest for Gunder and Camp Creek, and weakest for Roberts Creek. This trend may indicate that mass wasting may be a more important erosional process for Roberts Creek, compared with fluvial erosion.

Our recorded total streambank recession rates of 12.3 cm yr$^{-1}$ (Year 1) and 6.3 cm yr$^{-1}$ (Year 2) (Table 2.5) fell within the range of recession recorded during a previous Walnut Creek study [14]. During that study, total bank recession rates averaged 18.8 cm yr$^{-1}$ over a five year period, with a minimum of -0.64 and a maximum of 34.2 cm yr$^{-1}$.

2.4.3 Sediment and TP Mass Losses

Camp Creek exhibited the greatest watershed-scale sediment mass loss among alluvial units (Figure 2.9). No significant difference was detected between units, however, most likely
due to high variability among individual bank readings. This trend differs from that seen in the recession analyses, where Gunder exhibited a significantly higher recession rate and cumulative recession than Camp Creek. NMM Net contributed the greatest sediment mass of any streambank material, nearly 2.5 times the mass contributed by Camp Creek, Roberts Creek, and Gunder combined. This trend points to the importance of surface area representation, as NMM Net exhibited lower recession rate and cumulative recession than any alluvial unit. Total bank sediment mass contribution closely followed the temporal trends of NMM Net (Figure 2.10), again underscoring the importance of streambank surface area representation in terms of potential load contributions. Alluvial units, however, contributed greater sediment mass per unit surface area than NMM Net, especially Gunder (Figures 2.9, 2.10, Table 2.4). Gunder may be expected to contribute more mass per surface area, due to its relatively high bulk density and greater recession (Table 2.3, Figures 2.7, 2.8). Sediment mass contributions may be influenced temporally by stratigraphy. Because of position, material that comprises the bank toe (i.e., Gunder, NMM) may act as an immediate source of sediment to waterways once eroded. Mass losses from upper units (i.e., Camp Creek, Roberts Creek), however, may be stored as NMM following detachment, thus acting as a longer-term source of sediment as compared with losses from a lower stratigraphic position.

Trends in TP mass loss closely follow those of sediment mass. As with sediment mass, NMM Net TP mass contribution was nearly double than the combined contributions of Camp Creek, Roberts Creek, and Gunder (Figures 2.11, 2.12). As opposed to sediment mass trends, Gunder represented the greatest TP mass contributor among alluvial units, being significantly higher than contributions of Camp Creek and Roberts Creek (Figure 2.11). This is most likely due to Gunder’s greater TP concentration (Table 2.3). Similar to sediment mass trends, alluvial
units contributed more TP per unit surface area than NMM Net, with Gunder again contributing the most TP per unit surface area of the alluvial units (Figures 2.11, 2.12, Table 2.3).

At time of publication, Walnut Creek suspended sediment and TP loads for Year 1 and Year 2 were not yet quantified. However, Palmer et al. [14] previously reported Walnut Creek annual suspended sediment loads ranging from 6172 to 25,815 Mg with streambank contributions ranging from 1.5 to 53% of watershed loads. Our calculated total bank sediment losses for Year 1 and Year 2 were 2710.5 and 1049.3 Mg, respectively. Our reported losses would equate to between 4.0 and 43.9% of annual loads reported by Palmer et al. [14]. When estimated by individual units, sediment losses would equate to 0.4-8.0% (Camp Creek), 0.1-4.6% (Roberts Creek), 0.5-6.1% (Gunder) and 3.1-27.3% (NMM Net) of previously reported annual loads.

No TP loads were reported during the previous Walnut Creek study, however, Schilling et al.[40] reported Walnut Creek annual TP loads ranging from 1.7 to 9.0 Mg yr⁻¹ for years 2000 through 2005. In the context of these data, total streambank annual TP mass losses measured in this study would be equivalent to between 2.7 and 37.5% of annual loads. Individual alluvial unit contributions would range from <0.1 to 6.7%. Our streambank suspended sediment and TP load contribution estimates fall within ranges reported in the literature [5,6,8,15,21], however, they occupied the mid-to-lower end of the spectrum.

2.5 Conclusions

The three members of the Holocene DeForest Formation that comprise Walnut Creek streambanks (i.e., Camp Creek, Roberts Creek, Gunder) represented a relatively small proportion of total streambank-face surface area, and were relatively minor contributors to the overall sediment and TP mass losses coming from streambanks. Individual member (i.e.,
alluvial unit) mass losses equated to between 0.1 and 8% of historic annual watershed suspended sediment loads, and between <0.1 and 6.7% of historic annual watershed TP loads. Non-member material (NMM) dominated the streambank-face surface area and contributed the majority of sediment and TP mass streambank losses. NMM is a mixture of colluvium, weathered member material, and alluvium that frequently draped portions of banks. Specific alluvial units exhibited significantly greater net recession rates, cumulative recession, and represented a greater sediment and TP source per unit surface area versus NMM. However, the dominance of bank surface area by NMM resulted in NMM acting as the primary source material for sediment and TP losses from streambanks.

Stratigraphic position may have played a significant role in the recession and resulting sediment and TP losses of alluvial units, and should be considered in future research intent on quantifying sediment and TP contributions from streambanks. Position will determine frequency and duration of alluvial unit contact with eroding streamflow, as well as the degree to which each unit is impacted by varying erosional processes (e.g., fluvial, subaerial, mass wasting). Although alluvial unit sediment mass contribution to overall bank losses was minor, further research is needed as to the proportional impact these specific materials will have on in-stream P dynamics once eroded.

2.6 Acknowledgements

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2.8 Tables, Figures, and Equations

Figure 2.1. Location of watershed, monitored channel length, and streambank sites, Walnut Creek, Iowa, USA.

Figure 2.2. Floodplain cross section depicting stratigraphic position and scale of streambank alluvial units, Walnut Creek, Iowa. Image adapted from Schilling et al. [27].
Figure 2.3. Photograph depicting stratigraphic position and scale of streambank alluvial units, Walnut Creek, Iowa. Photo credit: Hanna McBrearty, Iowa State University.
Figure 2.4. Extracted soil that highlights the color and texture of the Camp Creek, Roberts Creek, and Gunder alluvial streambank units, Walnut Creek, Iowa. Photo credit Hanna McBrearty, Iowa State University.
Figure 2.5. A streambank with all four materials of interest present, Walnut Creek, Iowa. Note the fully exposed Camp Creek and partially exposed Roberts Creek. The Gunder was completely draped by non-member material (NMM), and exposed using a shovel. Photo credit: Hanna McBrearty, Iowa State University.

Figure 2.6. Study duration daily mean discharge (m$^3$ sec$^{-1}$) measured at watershed outlet, Walnut Creek, Iowa. Data from USDA-ARS.
Figure 2.7. Mean individual pin daily erosion rate (mm day\(^{-1}\)) by alluvial unit, NMM Gross, and NMM Net, Walnut Creek, Iowa. Lower-case letters indicate significant difference between units (p-value < 0.05).

Figure 2.8. Cumulative lateral recession by alluvial unit (cm), NMM Gross, and NMM Net, Walnut Creek, Iowa. Lower-case letters indicate significant difference between units (p-value < 0.1).
Figure 2.9. Cumulative mean sediment mass loss for Camp Creek, Roberts Creek, and Gunder alluvial units, for the main stem of Walnut Creek, Iowa. Significant differences (p-value < 0.1) indicated by differing lower-case letters. Error bars omitted for clarity.

Figure 2.10. Cumulative mean sediment mass loss for NMM Net and total bank, for the main stem of Walnut Creek, Iowa.
Figure 2.11. Cumulative mean TP mass loss for Camp Creek, Roberts Creek, and Gunder alluvial units, for the main stem of Walnut Creek, Iowa. Significant differences (p-value < 0.1) indicated by differing lower-case letters. Error bars omitted for clarity.

Figure 2.12. Cumulative mean TP mass loss for NMM Net and total bank, for the main stem of Walnut Creek, Iowa.
Figure 2.13. Correlation between total pin measurement period discharge (Total Q) and measurement period mean pin recession rate (Recession), and correlation between maximum pin measurement period discharge (Max Q) and pin measurement period mean recession rate (Recession Rate) for streambank materials, Walnut Creek Iowa. Spearman’s rank correlation coefficient denoted as Spearman’s ρ.

Table 2.1. The four erosional scenarios used to assign specific material to an individual streambank pin recession measurement, Walnut Creek, Iowa.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Material present at previous measurement</th>
<th>Material present at current measurement</th>
<th>Assign</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NMM</td>
<td>NMM</td>
<td>NMM</td>
</tr>
<tr>
<td>2</td>
<td>NMM</td>
<td>Unit</td>
<td>NMM</td>
</tr>
<tr>
<td>3</td>
<td>Unit</td>
<td>NMM</td>
<td>NMM</td>
</tr>
<tr>
<td>4</td>
<td>Unit</td>
<td>Unit</td>
<td>Unit</td>
</tr>
</tbody>
</table>
Table 2.2. Precipitation, hydrology, and eroding streambank length data for Walnut Creek, Iowa, for May 2015 to April 2017. Year 1 represents April, 2016 streambank eroding length assessment data, Year 2 represents March, 2017 streambank eroding length assessment data. 1Percent of total main stem streambank length classified as severely or very severely eroding (USDA-NRCS).

<table>
<thead>
<tr>
<th>Period</th>
<th>Duration (days)</th>
<th>Total Precipitation (mm)</th>
<th>Annual Mean Daily Discharge (m³ sec⁻¹)</th>
<th>Maximum Mean Daily Discharge (m³ sec⁻¹)</th>
<th>Total Discharge (m³)</th>
<th>¹Main stem eroding length (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1 (May 2015–April 2016)</td>
<td>358</td>
<td>1118</td>
<td>0.71</td>
<td>11.28</td>
<td>22,099,904</td>
<td>25.1</td>
</tr>
<tr>
<td>Year 2 (May 2016–April 2017)</td>
<td>371</td>
<td>977</td>
<td>0.43</td>
<td>5.43</td>
<td>13,667,103</td>
<td>16.1</td>
</tr>
</tbody>
</table>

Table 2.3. Mean total phosphorus concentration and soil parameters of alluvial units, Walnut Creek, Iowa. Non-member material denoted by NMM. Silt-clay content by weight denoted by SC. Water stable macro-aggregates by weight denoted by WSA. Numbers in parentheses indicate standard errors.

<table>
<thead>
<tr>
<th>Alluvial Unit</th>
<th>TP (mg kg⁻¹)</th>
<th>SC (%)</th>
<th>Bulk density (g cm⁻³)</th>
<th>WSA &gt;2mm (%)</th>
<th>WSA &gt;0.25mm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camp Creek</td>
<td>170.8 (12.8)</td>
<td>94.0 (1.1)</td>
<td>1.30 (0.04)</td>
<td>11.3 (1.3)</td>
<td>44.9 (2.6)</td>
</tr>
<tr>
<td>Roberts Creek</td>
<td>197.9 (33.8)</td>
<td>91.2 (2.0)</td>
<td>1.27 (0.02)</td>
<td>21.5 (4.0)</td>
<td>68.7 (3.5)</td>
</tr>
<tr>
<td>Gunder</td>
<td>304.2 (62.5)</td>
<td>71.5 (7.1)</td>
<td>1.60 (0.04)</td>
<td>3.8 (0.7)</td>
<td>15.5 (2.7)</td>
</tr>
<tr>
<td>NMM</td>
<td>241.4 (10.4)</td>
<td>80.9 (1.9)</td>
<td>1.20 (0.02)</td>
<td>12.2 (3.2)</td>
<td>31.0 (3.6)</td>
</tr>
</tbody>
</table>
Table 2.4. Alluvial unit surface area representation within eroding streambank faces for Year 1 (May 2015 – April 2016) and Year 2 (May 2016 – April 2017) for main stem of Walnut Creek, Iowa. Numbers in parentheses indicate standard errors. 

<table>
<thead>
<tr>
<th>Alluvial Unit</th>
<th>% SA</th>
<th>% SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camp Creek</td>
<td>11.2 (2.4) a</td>
<td>7.2 (1.2) a</td>
</tr>
<tr>
<td>Roberts Creek</td>
<td>5.8 (2.4) ab</td>
<td>3.2 (2.1) bc</td>
</tr>
<tr>
<td>Gunder</td>
<td>3.6 (1.1) b</td>
<td>2.5 (1) c</td>
</tr>
<tr>
<td>NMM</td>
<td>79.4 (4.9) c</td>
<td>87.1 (3.4) d</td>
</tr>
</tbody>
</table>

Data from August 2015 survey. 

Data from August 2016 survey. Within years, differing lower-case letters indicate significant difference in surface area (p-value < 0.1) between units.

Table 2.5. Total Bank cumulative mean recession for Year 1, Year 2, and study duration, Walnut Creek, Iowa. Results derived from individual bank cumulative recession data. Numbers in parentheses represent standard error.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Mean (cm)</th>
<th>Minimum (cm)</th>
<th>Maximum (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1 (May 2015 – April 2016)</td>
<td>12.3 (2.6)</td>
<td>1.8</td>
<td>27.9</td>
</tr>
<tr>
<td>Year 2 (May 2016 – April 2017)</td>
<td>6.3 (1.4)</td>
<td>0.6</td>
<td>14.4</td>
</tr>
<tr>
<td>Study Duration (May 2015 – April 2017)</td>
<td>18.6 (3.8)</td>
<td>6.0</td>
<td>42.3</td>
</tr>
</tbody>
</table>
\[
(Mean\ unit\ recession\ (m) \times Total\ unit\ surface\ area\ (m^2)) \times (Mean\ bulk\ density\ (kgm^{-3})) = Unit\ sediment\ mass\ contribution\ (kg)
\]

*Equation 2.1. Watershed-scale sediment mass contribution per individual unit, per pin measurement period.*

\[
(Unit\ sediment\ mass\ contribution\ (kg) \times Mean\ unit\ TP\ concentration\ (mgkg^{-1})/(1 \times 10^6))
\]

\[
= Unit\ TP\ mass\ contribution\ (kg)
\]

*Equation 2.2. Watershed-scale TP mass contribution per individual unit, per pin measurement period.*
CHAPTER 3. CHANGES IN LATERAL FLOODPLAIN CONNECTIVITY
ACCOMPANYING STREAM CHANNEL EVOLUTION: IMPLICATIONS FOR
SEDIMENT AND NUTRIENT BUDGETS

A manuscript prepared for submission to Science of the Total Environment

William J. Beck, Peter L. Moore, Keith E. Schilling, Calvin F. Wolter, Thomas M. Isenhart, Kevin J. Cole, and Mark D. Tomer

Abstract

Floodplain storage commonly represents one of the largest sediment fluxes within sediment budgets. In watersheds responding to large scale disturbance, floodplain-channel lateral connectivity may change over time with progression of channel evolution and associated changes in channel geometry. In this study we investigated the effects of channel geometry change on floodplain inundation frequency and flux of SS and TP to floodplain storage within the 5218 ha Walnut Creek watershed (Iowa, USA) through a combination of 25 in-field channel cross section transects, hydraulic modeling (HEC-RAS), and stream gauging station-derived water quality and quantity data. Channel cross sectional area increased by 17% over the 16 year study period (1998 – 2014), and field data indicate a general trend of degradation and widening (stage IV channel evolution) to be present along Walnut Creek’s main stem. Estimated stream discharge required to generate lateral overbank flow increased 15%, and floodplain inundation volume decreased by 37% over study duration. Flux of SS and TP to floodplain storage decreased by 24 and 26% over study duration, respectively. The estimated reductions in flux to floodplain storage have potential to increase watershed export of SS and TP by 8 and 16%, respectively. Increased contributions to SS and TP export may continue as channel evolution progresses. Thus, it is
critical that stage and progression of channel evolution be taken into consideration when addressing sediment and phosphorus loading at the watershed scale.

3.1 Introduction

Connectivity between a stream channel and its floodplain through lateral overbank flow represents a vital pathway for the transfer and exchange of energy and materials between aquatic and terrestrial ecosystems (Tockner et al., 1999; Bayley, 2014). This link has significant impacts on the life cycle and functioning condition of aquatic (Phelps et al., 2015) and terrestrial biota (Allen et al., 2016; Kaase and Kupfer, 2016; Batzer et al., 2018). Connectivity provides a myriad of ecosystem services for society as well, notably the detention of flood waters (Tockner and Stanford, 2002). A service of particular importance is the ability of floodplains to trap and store sediment and nutrients delivered with inundating overbank flow (Venterink et al., 2003; Noe and Hupp, 2009; Hopkins et al., 2018). Floodplain storage has been documented as a significant component of watershed sediment budgets (Walling et al., 1998), especially in systems experiencing aggradation in response to disturbance (Trimble, 1983). Floodplains have also been documented to store significant amounts of phosphorus (P) that enter from inundating overbank flows (Kronvang et al., 2007), as P often moves in association with sediment. Thus, the degree of channel-floodplain connectivity may have important implications for sediment and P budgets, as well as export, at the watershed scale.

A hydrologic separation between the channel and floodplain frequently occurs when changes in channel geometry increase channel conveyance. This change can occur naturally over millennia (e.g., following climatic shifts) or rapidly as a response to anthropogenic disturbance (e.g., channelization). In alluvial channels, response to disturbance occurs through a relatively consistent pattern of adjustments collectively known as the channel
evolution model (CEM) (Schumm et al., 1984; Simon, 1989). These adjustments are frequently initiated by an increase in stream power and/or decrease in sediment supply relative to previous conditions. The initial response is for the channel to incise (referred to as stage III), followed by subsequent stages of degradation and widening (IV), and aggradation and widening (Stage V) before returning to relative stability (stage VI). Several studies from the U.S. Midwest (Schilling and Wolter, 2000; Palmer et al., 2014; Beck et al., 2018; Zaimes et al., 2004; Belmont et al., 2011; Midgley et al., 2012; Tufekcioglu et al., 2012; Willett et al., 2012) have documented unstable in-channel conditions (e.g., channel incision, streambank erosion) that suggest regional streams are experiencing adjustment-driven increases in cross-sectional area.

If all else remains equal, the adjustment-driven increase in channel cross-sectional area should lead to a corresponding increase in the maximum discharge that can be contained within the channel. We’ll refer to this discharge as \( Q_t \), as it is the threshold discharge above which portions of the floodplain may become inundated. A preliminary estimate of the magnitude of change in \( Q_t \) accompanying a change in channel cross-sectional area may be outlined using a strategy similar to that of Moody et al., 1999 (Equation 4). Suppose that the depth \( d \) of an evolving channel changes by a factor of \( \lambda \), (so that \( d_2 = \lambda d_1 \) ) and width \( w \) changes by a factor \( \theta \) (so that \( w_2 = \theta w_1 \)) between two observations, time 1 and time 2. According to Manning’s equation \( Q = n^{-1}d^{5/3}wS^{1/2} \), the ratio of thresholds discharges between time 2 and time 1 is:

\[
\frac{Q_{t2}}{Q_{t1}} = \left( \frac{\theta w_1}{w_1} \right) \left( \frac{\lambda d_1}{d_1} \right)^{5/3} = \theta \lambda^{5/3},
\]
assuming no change in channel roughness \((n)\) or gradient \((S)\). From this equation, a hypothetical 10% increase in channel depth \((\lambda = 1.1)\) and a 10% increase in channel width \((\theta = 1.1)\) would lead to a nearly 29% increase in threshold discharge \((1.1 \times 1.1^{5/3} = 1.289)\).

This estimate, however, assumes uniform and steady flow, which may be a poor approximation in real streams, particularly those that exhibit flashy hydrology. It nevertheless suggests that relatively small changes in channel cross-sectional area could have substantial effects on the discharge necessary to access the floodplain.

If floodplain inundation frequency and extent decrease as a channel progresses through stages III-V, a significant reduction in floodplain storage of suspended sediment (SS) and total phosphorus (TP) may occur. This reduction in floodplain storage is of importance, as it may lead to increases in watershed-scale SS and TP export. Thus, proper understanding and inclusion of geomorphological processes, such as changes in channel geometry, is critical when developing budgets and allocating sources of SS and TP. Despite this, proper understanding and inclusion of geomorphological processes is frequently lacking in watershed-scale budgets (Reid and Dunne, 2003). In addition, studies that investigate floodplain inundation dynamics and flux of SS and TP to floodplain storage at the watershed scale are rare, due in part to the complexity of floodplain-channel interactions and computational effort required for modeling at that respective scale (Nicholas et al., 2006).

For this study, we seek to estimate watershed-scale overbank flow dynamics and flux of SS and TP to floodplain storage in the context of channel evolution. We utilize a combination of in-field channel cross section measurements, hydraulic modeling, and stream gauging station-derived water quality and quantity data to investigate changes in floodplain inundation and storage over a 16 year period in Walnut Creek, Iowa, USA. We hypothesize
that the increased channel cross sectional area should increase the bankfull capacity of the channel. Without a corresponding increase in the duration of high-discharge events, this should reduce frequency of floodplain inundation and therefore reduce opportunities to store sediment and nutrients on the floodplain.

Our specific study objectives were to: 1) characterize channel geomorphic change along ~10 km of alluvial stream channel over a 16 year period; 2) estimate the effects of channel geomorphic change on overbank flow parameters and channel-floodplain connectivity at the watershed scale; 3) estimate the effects of channel geomorphic change on flux of suspended sediment and total phosphorus to floodplain storage at the watershed scale, and 4) assess the implications of channel geomorphic change on watershed-scale SS and TP budgets.

3.2 Materials and Methods

3.2.1 Study Area

3.2.1.1 Watershed description

Walnut Creek is a perennial, third order stream draining 5218 ha in Jasper County, Iowa, USA (Figure 3.1). The Walnut Creek watershed is located in the Rolling Loess Prairies Level IV Ecoregion (47f), a region typified by rolling topography and well-developed drainage systems (Griffith et al., 1994). Walnut Creek is located within a humid, continental region with average annual precipitation of approximately 750 mm. Watershed land use consists of 54% rowcrop agriculture (primarily corn-soybean rotation), 36% grassland, and 4% forest, with the remainder comprising roads, farmsteads, and urban areas (Schilling et al., 2006). Of the grassland area, 25.4% is recently restored tallgrass prairie established by the U.S. Fish and Wildlife Service (USFWS) as part of the Neal Smith National Wildlife Refuge
55

(NSNWR). Since refuge creation in 1991, large tracts of row crop agricultural land have been converted to native tallgrass prairie.

Watershed soils are primarily silty clay loams, or clays formed in loess or till. The upland surficial geology is comprised of a 1-6 m loess cap overlaying pre-Illinoian glacial till, with Holocene alluvial deposits being comprised primarily of silty clay loams, clay loams, or silt loams (Schilling et al., 2009). A majority of watershed soils exhibit moderate to high erosion potential, with 54% being classified as highly erodible (Schilling and Thompson, 2000).

**3.2.1.2 Channel and floodplain characteristics**

The Walnut Creek channel is incised more than 3 m into its floodplain and is typified by tall, cohesive (i.e., >15% clay content) streambanks (Photo 3.1). The effects of historic agricultural-associated practices such as row crop conversion, stream straightening, subsurface drainage, and removal of riparian vegetation (Schilling and Wolter, 2000; Schilling et al., 2011), have led to a flashy hydrology, with Walnut Creek frequently exhibiting rapid responses to precipitation. Several stages of stream channel evolution have been documented through ~20 years of channel cross sectional measurements initiated by Schilling and Wolter (2000), with areas of Stage III (degradation), Stage IV (degradation and widening), and Stage V (aggradation and widening) present (Simon, 1989). Field observations indicate Stage IV as the most prevalent along Walnut Creek’s main stem (Photo 3.2).

Walnut Creek’s floodplain is comprised of a series of loess-derived Holocene alluvial deposits, collectively known as the DeForest Formation (Bettis, 1990). Three primary members of the DeForest Formation comprise the vertical profile of Walnut Creek’s floodplain. The Gunder member occupies the lowest stratigraphic position at depths of 1-3 m
(Schilling et al., 2009) and commonly comprises the streambank toe and streambed. The Gunder has been classified as a silt loam with massive structure, and exhibits a greater bulk density (1.6 g cm$^{-3}$) and sand content (28.5% by weight) relative to the other members (Beck et al., 2018). The Roberts Creek member (silty clay loam) overlies the Gunder, and represents the pre-European-American settlement landscape surface (Bettis et al., 1992). The Camp Creek member overlies the Roberts Creek and represents the upper stratigraphic position (i.e., floodplain surface). Camp Creek was deposited during the last ~400 years (Bettis et al., 1992), and is typically referred to as ‘post-European-American settlement alluvium’. Camp Creek is described as a silt loam, and ranges in thickness from 0.6 to 1.8 m (Schilling et al., 2009). Distribution, stratigraphic position, thickness, and inherent soil characteristics (e.g., texture, bulk density) of the Camp Creek, Roberts Creek, and Gunder members have been documented as being consistent throughout the watershed (Schilling et al., 2009).

Monocultural expanses of reed canary grass (*Phalaris arundinacea*) dominate the current vegetative cover of Walnut Creek’s floodplain. These expanses are frequently interspersed with low-density riparian forest, comprised primarily of Eastern Cottonwood (*Populus deltoides* Bartr.), Silver Maple (*Acer saccharinum* L.), Green Ash (*Fraxinus pennsylvanica* Marsh.), Black Walnut (*Juglans nigra* L.), Hackberry (*Celtis occidentalis* L.), White Mulberry (*Morus alba* L.), and Black Willow (*Salix nigra* Marsh.). Along the outer floodplain fringe, landcover transitions to a mixture of row crop agriculture (i.e., corn-soybean rotation) and re-established native tallgrass prairie with increasing floodplain surface elevation.
3.2.2 Field Measurements

During October 1998, researchers traversed ~10 km of Walnut Creek’s main stem and established a series of 25 stream channel cross section transects (Schilling and Wolter, 2000) (Figure 3.1). Transects were spaced every ~300 to 400 m, with locations selected to represent the range of channel form (e.g., meandering, straight) and condition (e.g., erosion activity, bed material) present in Walnut Creek. Cross sectional dimensions were measured by stretching a meter tape across the top of banks, perpendicular to the channel, and using a survey rod to record lateral distance along the tape and depth from the tape to the channel walls and streambed. Length-depth readings were recorded at each significant break in slope, as well as left and right edges of water and at the thalweg. End points for the cross-section locations were established using GPS-technology. During October 2014, transect locations were revisited and cross sectional dimensions measured using the identical rod-tape method.

3.2.3 Evaluation of Channel-Floodplain Lateral Connectivity

3.2.3.1 HEC-RAS models

Walnut Creek floodplain inundation frequency, discharge, and extent for the years 1998 and 2014 were quantified through creation of a pair of Hydrological Engineering Center River Analysis 5.0.1 (HEC-RAS) models (U.S. Army Corps of Engineers, 2016). HEC-RAS is a hydraulic model that uses the one-dimensional energy equation to calculate water surface elevations at a series of channel cross sections for given river discharge values. HEC-RAS was deemed an effective means of quantifying channel-floodplain connectivity as its outputs include floodplain inundation depth (m), velocity (m s\(^{-1}\)), and discharge (m\(^3\) s\(^{-1}\)) at individual channel cross sections, as well as cumulative floodplain inundation volume (m\(^3\)) and areal extent (m\(^2\)) for river reaches as a whole. The overbank flow duration outputs generated by HEC-RAS were used as a means to quantify change in floodplain SS and TP.
storage in light of the lack of widespread depositional field data available to researchers at time of study.

Individual HEC-RAS models were created for the years 1998 and 2014, and entailed merging respective field cross section transects with a 3m digital elevation model (DEM). Lateral extents of field cross section transects were increased to span the entire left and right overbank floodplains. Models represented the entire ~10 km study length of Walnut Creek’s main stem, which was divided into 7 individual reaches based on confluences with significant tributaries (Figure 3.1). Reaches ranged in length from 264 to 2408 m. Inclusion of tributary flow allowed for 100% of watershed contributing area to be accounted for within the models. Manning’s roughness coefficient ($n$) inputs for channel cross sections and floodplain areas were determined using an additive method outlined in Arcement and Schneider (1989). Model simulations were conducted under steady flow conditions (i.e., no change in discharge with time at individual cross sections) and subcritical (i.e., Froude number < 1.0) flow regimes.

HEC-RAS requires stream discharge inputs for each individual channel cross section. Discharge inputs for this study were derived from United States Geological Survey (USGS) and United States Department of Agriculture Agricultural Research Service (USDA-ARS) sub-hourly discharge data collected at the watershed outlet gauging station (Figure 3.1). Sub-hourly discharge data were averaged to an hourly time series, and then used to create a flow duration curve (FDC) for the data availability period (1994 – 2017). FDCs display the percent of time that a particular stream discharge is exceeded over a given time period (Vogel et al., 1994). A mean hourly discharge time series was utilized to best capture rapid stormflow peaks characteristic of Walnut Creek’s flashy hydrology. Mean hourly discharges
were scaled from the watershed outlet gauging station to individual cross sections using discharge-drainage area relations (Biedenharn et al., 2000; Linhart et al., 2012). Discharge-drainage area estimates of cross-section discharge were validated using the FDC (1994-2017) of Walnut Creek’s upstream gauging station.

### 3.2.3.2 Overbank threshold discharge

A range of higher-discharge (~10 to 71 m$^3$ s$^{-1}$) stream flows were selected from the overall FDC and used as HEC-RAS inputs in an exploratory effort to identify overbank discharge thresholds for all individual cross sections in both models. The overbank threshold discharge for an individual channel cross section was defined as the discharge required to initially force streamflow to exit the channel and enter the floodplain on at least on side of the channel. Authors recognize that floodplain inundation could occur via saturation-overland flow from adjacent upland areas, however, for the purposes of this study we consider SS and TP flux to the floodplain to occur only when a direct hydraulic connection between channel and floodplain exists.

Threshold determination for each cross section was achieved through visual (e.g., RAS Mapper) and numerical interpretation of HEC-RAS outputs. Threshold discharges were determined for both individual cross sections, as well as at the watershed-scale. Three watershed-scale thresholds were calculated for each model, and were represented by the watershed outlet mean hourly discharge: 1) stream discharge required to produce overbank flow at 100% of cross sections (hereafter referred to as *maximum discharge*), 2) stream discharge required to produce overbank flow at the majority (i.e., >50%) of cross sections (hereafter referred to as *majority discharge*), and 3) stream discharge at which only one cross section remains overbank (hereafter referred to as *minimum discharge*).
3.2.3.3 Floodplain storage

Floodplain storage quantification was initiated by selecting a range of watershed outlet FDC-derived discharge values as HEC-RAS inputs (Table 3.1). In the HEC-RAS models, input discharge values were associated with a respective FDC-derived percent exceedance. Hereafter, these specific combinations of discharge and percent exceedance will be referred to as discharge profiles. HEC-RAS numerical outputs allow for quantification of floodplain discharge (m$^3$ s$^{-1}$), floodplain inundation areal extent (m$^2$), and floodplain inundation volume (m$^3$) at individual cross sections for specific discharge profiles. Individual cross section results were summed to estimate overbank values for each stream reach, as well as the entire main stem floodplain of Walnut Creek.

Suspended sediment and TP rating curves were developed using USDA-ARS stormflow grab sample data collected at the watershed outlet stream gauging station between 2008 and 2017. The predictive equations were used to estimate SS and TP concentrations for all HEC-RAS discharge profiles. These concentrations were applied to floodplain inundation volumes to estimate flux of SS and TP from channel to floodplain for each discharge profile using the equation:

\[
S_{fp} = \sum_{i=1}^{n} E c_i Q_i \left[ \frac{Q_i - Q_t}{Q_t} \left( 1 - \frac{w}{f} \right) \right]
\]

where $S_{fp}$ is mass flux to floodplain storage (Mg), $n$ is number of discharge profiles, $E$ is the floodplain trapping efficiency, $c_i$ is concentration at discharge profile $i$ (kg m$^{-3}$), $Q_i$ is stream discharge at discharge profile $i$ (m$^3$ s$^{-1}$), $Q_t$ as before is overbank threshold discharge (m$^3$ s$^{-1}$), $w$ is channel width (m) and $f$ is width of inundated floodplain (m). To estimate the
percentage of overbank flux that entered floodplain storage, a floodplain trapping efficiency component \((E)\) was applied to all overbank SS and TP fluxes using the equation:

\[
E = 1 - e^{-\omega \left( \frac{A}{Q_{t}-Q_{i}} \right)}
\]

where, \(E\) is the floodplain trapping efficiency, \(\omega\) is particle settling velocity \((\text{mm s}^{-1})\), and \(A\) is the areal extent of floodplain inundation \((\text{m}^2)\). The estimate of trapping efficiency was based on the method introduced by Chen (1975), which has been successfully utilized in other floodplain sedimentation studies (Asselman and Van Wijngaarden, 2002; Narinesingh et al., 1999). Particle settling velocity was estimated using the relationship developed by Thonon et al. (2005):

\[
\omega = aD^b,
\]

where \(D\) is particle diameter \((\mu\text{m})\), and \(a (2.7 \times 10^{-4})\) and \(b (1.57)\) are constants. The Thonon equation was selected because it utilizes a single representative grain size. As suspended sediment grain size distribution data was unavailable at time of study, researchers used the Camp Creek median grain size \((D_{50})\) of 30 \(\mu\text{m}\) (Beck et al., 2018) as the representative suspended sediment grain size. As mentioned in sub-section 3.2.1.2, Camp Creek represents the uppermost stratigraphic floodplain unit. Although grain size distribution of deposited sediment may differ significantly from the grain size distribution of SS, the Camp Creek \(D_{50}\) was deemed the best available estimate for the current study. The selected representative grain size of 30 \(\mu\text{m}\) falls within a range that has been successfully used for the same purpose in other floodplain sedimentation studies (Asselman, 1999; Asselman and Van Wijngaarden, 2002; Middelkoop and Van der Perk, 1998). For this study, TP was assumed to move with SS, thus one value of \(E\) was utilized for both SS and TP.
To elucidate the effects of channel adjustment on floodplain inundation frequency and floodplain SS and TP storage, the series of discharge profiles were run in both the 1998 and 2014 HEC-RAS models. Model outputs were used to quantify floodplain discharge (m$^3$ s$^{-1}$), width of floodplain inundation (m), floodplain inundation areal extent (m$^2$), floodplain inundation volume (m$^3$), and the resulting SS and TP floodplain storage masses (Mg) for between-model comparisons.

### 3.2.4 Laboratory and Statistical Methods

Stormflow surface water samples were collected as grab samples at the watershed outlet stream gauging station by USDA-ARS staff and analyzed for SS and TP at the USDA-ARS National Laboratory for Agriculture and the Environment (NLAE). Analysis for SS was performed by whole sample gravimetric analysis (ASTM, 2000). Analysis for TP was performed using persulfate digestion, with P concentrations determined by colorimetric analysis using a spectrophotometer.

Simple linear regression and the Mann-Kendall trend test were performed on flow duration curve data to detect any temporal trends in the hydrologic regime (Helsel and Hirsch, 2002). Suspended sediment and TP rating curve predictive equations were developed using simple linear regression methods outlined in Rasmussen et al (2011). Regression analysis utilized log (base 10) transformations of both explanatory (i.e., discharge) and response variables (i.e., SS, TP), as well as Duan’s bias correction factor (Duan, 1983). Wilcoxon signed-rank tests were used to test for differences in overbank parameter outputs between the 1998 and 2014 models. All statistical procedures were performed using R v. 3.4.1 (R Core Team, 2017).
3.3 Results

3.3.1 Channel Dimensions

Surveyed channel cross sectional area increased by 16.8% between 1998 and 2014, with the majority (76%) of cross sections exhibiting degradation and widening (Figure 3.3). Change at individual cross section transects between 1998 and 2014 ranged from -12.8% (i.e., decrease in area) to >60% (Figure 3.4). Mean cross section width (top bank) increased by 9.5% from 1998 (10.5 m) to 2014 (11.5 m), and mean depth to thalweg (i.e., distance from top bank to channel bed at thalweg) increased 9.4% from 1998 (2.71 m) to 2014 (2.97 m). Cross section mean width/depth ratio was nearly identical (~3.9) for both years, with 1998 ratios ranging from 2.71 to 7.75, and 2014 ratios ranging from 2.8 to 5.8. For both years, cross section characteristics of depth to thalweg, width, and cross sectional area generally increased with distance downstream (i.e., drainage contributing area). Width/depth ratio, however, exhibited no spatial trend for both the 1998 and 2014 surveys. Change in channel cross section characteristics (i.e., width, depth, width/depth ratio, and area) between 1998 and 2014 also lacked an observable spatial pattern.

3.3.2 Hydrology

Linear regression (p < 0.001, $b_1 = 3.61 \times 10^{-7}$) and Mann-Kendall ($\tau = 0.016, p < 0.001$) tests for trend indicate an increase in mean hourly discharge between years 1995 and 2017. In contrast, visual analysis of ~5-year period flow duration curves (Figure 3.2) suggests lack of a systematic temporal trend in hydrologic regime between 1995 and 2017. It should be noted that 2007 – 2012 flow duration curve data (green line, Figure 3.2) include three exceptionally wet years (i.e., 2008, 2009, 2010), during which numerous mean hourly discharges greater than 40 m$^3$ s$^{-1}$ were recorded at the watershed outlet (<0.028% exceedance for 1995 – 2017 data period). In addition to the visual analysis suggesting no meaningful
change in hydrologic regime between 1995 and 2017, the slope for the increase in threshold majority discharge between 1998 and 2014 \( (2.52 \times 10^{-5}) \) was \(-115\) times greater than the mean hourly discharge slope detected in trend analyses. This suggests that the detected increase in streamflow most likely had a negligible impact on the change in channel conveyance, as compared to change in conveyance brought about by cross sectional area change. In addition, the regression analysis included all parts of the FDC, including baseflow. While it may be possible that the changes in lower magnitude flows, which have no chance of accessing the floodplain, account for the statistical trend, they can’t account for the top of bank threshold discharge brought about by cross sectional area change accompanying channel evolution.

The discharge-area relationship used to scale watershed outlet discharges to discharges at individual cross sections was validated using the upstream gauging station FDC. Discharge-area predictions for the upstream gauging station location fell within 5.5% of gauge-measured mean discharges, and thus the discharge-area scaling technique was determined to be an acceptable means of estimating cross section discharge.

3.3.3 Channel-Floodplain Lateral Connectivity

3.3.3.1 Overbank threshold discharges

Bankfull threshold discharges were found to increase between 1998 and 2014 (Figure 3.5). As described in subsection 3.2.3.2, the overbank threshold discharge was defined as the discharge required to initially force streamflow to exit the channel and enter the floodplain on at least one side of the channel. Minimum discharge (i.e., mean hourly watershed outlet discharge at which only one cross section remains overbank) increased \(28.9\%\) between 1998 \( (14.9 \text{ m}^3 \text{s}^{-1}) \) and 2014 \( (19.2 \text{ m}^3 \text{s}^{-1}) \) (Figure 3.6). Majority discharge (i.e., mean hourly watershed outlet discharge required to produce overbank flow at \(>50\%\) of cross-sections)
increased 14.9% between 1998 (24.2 m$^3$ s$^{-1}$) and 2014 (27.8 m$^3$ s$^{-1}$). Maximum discharge (i.e., mean hourly watershed outlet discharge required to produce overbank flow at 100% of cross sections) exhibited the lowest degree of change (12.9% increase) between 1998 (62.9 m$^3$ s$^{-1}$) and 2014 (71.0 m$^3$ s$^{-1}$).

The increase in threshold discharges represent shifts to lower (i.e., less frequent) threshold percent exceedances on the flow duration curve, with the majority discharge percent exceedance decreasing from 0.125% (1998) to 0.1% (2014) (Figure 3.7). Minimum discharge percent exceedance decreased from 0.25 to 0.175% between 1998 and 2014, and maximum discharge percent exceedance decreased from 0.0021 to 0.0011% over the same time period.

3.3.3.2 Floodplain storage trends

Trends in floodplain storage were evaluated by comparing the individual HEC-RAS flow simulations of all discharge profiles. Floodplain inundation volume (m$^3$) outputs for the 1998 HEC-RAS model were greater than 2014 model outputs (Figure 3.8 a.) for all discharge profiles (Table 3.1). Across all discharge profiles, main stem floodplain inundation volume ranged from 90 m$^3$ to 489,120 m$^3$ (mean of 156,738 m$^3$) for the 1998 model, and from 30 m$^3$ to 387,890 m$^3$ (mean = 98,460 m$^3$) for the 2014 model. This equates to a decrease of 58,278 m$^3$ (-37.2%) in mean volume between years. Predicted main stem floodplain inundation surface area (m$^2$) was also greater for the 1998 model (Figure 3.8 b.), with outputs from all discharge profiles ranging from 2470 m$^2$ to 798,690 m$^2$ (mean = 315,833 m$^2$) compared to the range of 20 m$^2$ to 694,870 m$^2$ (mean = 205,084 m$^2$) for the 2014 model. This equates to a decrease of 110,749 m$^2$ (-35.1%) in mean surface area between years.

The proportions of the floodplain experiencing inundation at individual cross section transects (normalized by floodplain width) were found to be significantly greater in 1998
than in 2014, for the top 6 (i.e., low frequency) discharge profiles (0.0005 < p < 0.05) (Figure 3.9). No significant difference was detected between 1998 and 2014 for the bottom 3 (i.e., most frequent) discharge profiles (0.58 < p < 0.59).

The 1998 model predicted greater fluxes of SS and TP to floodplain storage for all discharge profiles compared with the 2014 model (Figure 3.10). For all discharge profiles, flux of SS to floodplain storage ranged from 0.35 Mg to 3227.18 Mg (mean = 934.74 Mg) for the 1998 model, and from 0.006 Mg to 2967.61 Mg (mean = 712.95 Mg) for the 2014 model (Figure 3.10 a.). This equates to a decrease of 221.8 Mg (-23.7%) in mean SS mass storage between years.

Regarding SS storage per m channel length, the 1998 profile range represents 3.6 × 10^{-5} to 0.33 Mg m^{-1} SS (mean = 0.1 Mg m^{-1}), while the 2014 profile range represents 6.6 × 10^{-7} to 0.31 Mg m^{-1} (mean = 0.07 Mg m^{-1}), representing a 30% decrease (0.03 Mg m^{-1}) between years. Predicted TP flux to floodplain storage ranged from 3 × 10^{-4} to 2.03 Mg (mean = 0.62 Mg), and from 5.6 × 10^{-6} to 1.84 Mg (mean = 0.46 Mg) for the 1998 and 2014 models, respectively (Figure 3.10 b.). This equates to a decrease of 0.16 Mg (-25.8%) in mean TP mass storage between years. The 1998 profile range represents 3.1 × 10^{-8} to 2.1 × 10^{-4} Mg (mean = 6.4 × 10^{-5} Mg) TP storage per m channel length, while the 2014 profile range equates to 5.8 × 10^{-10} to 1.9 × 10^{-4} Mg (mean = 4.6 × 10^{-5} Mg) storage per m channel length. Between years, mean TP storage per m channel length decreased by 1.8 × 10^{-5} Mg (-28.1%).

When results of all discharge profile simulations were summed for each model to create a hypothetical annual series of flows, the 1998 model predicted an annual flux of 8412.6 Mg SS and 5.54 Mg TP to floodplain storage along the entire ~10 km of Walnut
Creek’s main stem. The 2014 model predicted fluxes of 6416.5 Mg (SS) and 4.13 Mg (TP), which represent decreases of 23.7 and 25.5% from 1998 results for the identical hypothetical series of flows.

Mean model-estimated floodplain trapping efficiency (across all profiles) decreased 33.1% between 1998 (50.9%) and 2014 (34.0%). Floodplain trapping efficiency (E) was calculated using Equation 3, in which area (A) of floodplain inundation extent (m²) is a significant driver of trapping efficiency.

3.4 Discussion

3.4.1 Channel Adjustment

Walnut Creek’s main stem increased in cross sectional area by an average of 16.8% (2.91 m²) between 1998 and 2014, which equates to an average annual rate of ~1% (0.18 m² yr⁻¹). Width and depth mean annual increases were 0.06 and 0.02 m yr⁻¹, respectively.

Although a limited number individual cross sections exhibited a decrease or negligible change in cross sectional area during that time period (Figure 3.4), a clear pattern of degradation and widening is present along Walnut Creek’s main stem.

Rates of channel dimensional change in Walnut Creek are lower than those reported in other loess-derived alluvial channels in the United States. Hamlett et al (1983) reported a 43% increase (0.29 m² yr⁻¹) in channel cross sectional area over a 16 year period (1964 – 1980) in the Four Mile Creek watershed, Iowa. Four Mile Creek has similar land area (5050 ha), floodplain soils (alluvial silt and clay) and disturbance impact (land cover alteration, channelization) as Walnut Creek, however, cross sectional measurements in Four Mile occurred much closer, temporally, to its reported period of maximum channel disturbance (mid to late 1970s). It is of note that Four Mile Creek rates of change recorded prior (i.e., mid to late 1960s) to the period of maximum disturbance more closely resembled rates reported
for Walnut Creek. In the Tarkio River watershed in western Iowa, (Simon and Rinaldi, 2006) reported 6-8 m of bed degradation over a period of ~100 years for loess derived alluvial channels, and an associated increase in channel width of 31 m. Similar to Four Mile Creek, the greatest rates of channel change occurred in the period immediately following maximum disturbance, with subsequent non-linear decreases in rate with time. Simon (1989) reported mean channel widening rates of 0.17 to 2.2 m yr\(^{-1}\), and a maximum bed degradation of 6.1 m for loess-derived alluvial channels in western Tennessee. These changes were observed approximately 5-24 years following the period of significant disturbance in study watersheds (i.e., wide spread channelization).

Rates of change in bed degradation in the Iowa and Tennessee studies follow a pattern of non-linear adjustment following disturbance (Schumm and Lichty, 1965; Graf, 1977). In other words, rates of change are greatest immediately following disturbance, and decrease non-linearly (i.e., power function) along an asymptote approaching critical stream power \((b_1 = 0)\) as time from disturbance increases (Simon, 1989, Figure 2). This pattern has been observed in a number of studies focused on channel response to disturbance (e.g., Williams and Wolman, 1984; Hadish 1994; Heine and Lant, 2009). It should be noted that the pattern of non-linear adjustment is associated with bed degradation, and not overall increase in channel cross sectional area. However, bed degradation is the primary driver of channel evolution, and widening does not occur until a critical point of incision is reached (i.e., point where banks become too tall to remain stable). Thus, a link does exist between degradation and channel cross sectional area increase (i.e., combination of degradation and widening).
In light of this, time since disturbance could be one reason why Walnut Creek rates are lower than other studies conducted in loess-derived alluvial channels. Walnut Creek measurements occurred between 1998 and 2014, ~40 to 80 years following period of maximum disturbance. Schilling and Drobney (2014) hypothesized that downcutting of Walnut Creek into its floodplain probably began to occur soon after settlement, and an early report of Walnut Creek indicated that by 1905, the channel had already undergone “considerable downcutting” (Williams, 1905). Since cross section data pre-1998 are lacking for Walnut Creek, it may be assumed that the channel is currently within the near-zero slope region (i.e., $b_1$ approaching 0) of the non-linear adjustment curve and although change in channel dimension is apparent, it is occurring at lesser rates than studies that report results closer, temporally, to respective periods of maximum disturbance.

In addition, rates of channel adjustment may be impacted by the presence of the Gunder member. As mentioned in subsection 3.2.1.2, the Gunder member represents the channel bed and streambank toe along a majority of Walnut Creek’s length. The Gunder is characterized by a relatively high bulk density (1.6 g cm$^{-3}$) and a mean clay content of 21% (Beck et al., 2018). Gunder critical shear stress (i.e., threshold stress applied by flowing water required to initiate erosion) has been documented as ranging from 10.4 (Layzell and Mandel, 2014) to 34.8 Pa (Beck et al., unpublished hydraulic flume data). In addition, Thomas et al (2009) documented the Gunder as having a relatively high mechanical shear strength (i.e., threshold force required for material deformation), ranging from 435 – 711 Pa. Thus, the Gunder possesses an inherent degree of resistance to fluvial erosion. The erosion resistance may be enhanced further for channel bed Gunder, as permanent saturation from streamflow may nearly eliminate the freeze-thaw and wet-dry cycles that would weaken
exposed Gunder (Hooke, 1979; Couper and Maddock, 2001). Thus, in Walnut Creek, the Gunder may act to regulate the degree of degradation and downcutting (Simon and Rinaldi, 2006), as opposed to Tarkio Creek and western Tennessee streams where deep loess deposits and lack of base level control promote unrestricted channel degradation. It is of note that Walnut Creek discharges to Red Rock reservoir approximately 10 km downstream of the watershed outlet gauging station, and thus a stabilized outlet elevation exists.

If Walnut Creek is in fact within the near-zero slope region of the non-linear adjustment curve, it may be further evidence for Stage IV of channel evolution (Simon, 1989). The assumption of Stage IV is supported by streambank angle (i.e., 70-90 degrees for vertical bank face, 25-50 degrees for upper bank), channel width/depth ratio (~3.9), and channel change (i.e., degradation and widening) data as well as visual evidence from the watershed (i.e., mass wasting).

3.4.2 Channel-Floodplain Connectivity

A simplistic uniform flow analysis (Equation 1) was used to predict the relationship between the 1998 and 2014 threshold overbank discharges. Equation 1 inputs of $\lambda$ (1.096) and $\theta$ (1.095) were derived from field measurements of mean cross section depth and width change between 1998 and 2014. Using these field-derived inputs, Equation 1 predicted the relationship between 1998 and 2014 threshold overbank discharges to be 1.27. In other words, using strictly Manning’s equation and field measured data of cross section width and depth change, the threshold overbank discharge was predicted to increase by 27% between 1998 and 2014.

Using the same field data as inputs, HEC-RAS outputs predicted increases in minimum, majority, and maximum threshold discharges of 28, 15, and 13%, respectively, between 1998 and 2014. Compared with the Manning’s results, HEC-RAS predicted smaller
increases in maximum and majority threshold discharges between 1998 and 2014. These differences likely reflect non-uniform flow effects and highlight the value of numerical hydraulic models such as HEC-RAS for inundation and sedimentation studies.

In general, connectivity between Walnut Creek and its floodplain decreased between 1998 and 2014. In 2014, flow events of greater discharge, and thus lower frequency of occurrence, would be required to maintain the same degree of floodplain connection (i.e., inundation volume, areal extent, SS and TP flux) observed in 1998. The mean increase in channel cross sectional area of 2.91 m$^2$ over the 16 year period was associated with a number of model-predicted changes to channel-floodplain connectivity in the Walnut Creek watershed. The minimum, majority, and maximum overbank threshold discharges all increased in magnitude, and decreased in percent exceedance (i.e., became less frequent) as more water was able to be conveyed within the channel. Majority discharge, for example, increased at an average rate of 0.23 m$^3$ s$^{-1}$ per year, while cross sectional area increased by an average of 0.18 m$^2$ per year. In 2014, the difference between majority discharge and minimum discharge was 8.54 m$^3$ s$^{-1}$. Using annual rates of change for majority discharge (0.23 m$^3$ s$^{-1}$) and cross sectional area (0.18 m$^2$), it would take an increase in channel cross section area of 6.72 m$^2$ to shift the 2014 majority discharge to the level of 2014 minimum discharge. At the current rate of channel enlargement (0.18 m$^2$ yr$^{-1}$), ~37 years would be required for the current majority discharge (27.75 m$^3$ s$^{-1}$) to become the minority discharge, at which ~50% of the Walnut Creek floodplain would lose connection with its channel for a significant portion of the flow regime (i.e., lower flows). Until large stretches of Walnut Creek’s channel transition to stage V (aggradation), connectivity between the channel and floodplain will continue to decline.
For each observed 1 m² increase in channel area between 1998 and 2014, floodplain inundation volume was observed to decrease by 3642 m³. In other words, a 1 m² increase in channel cross section area resulted in an additional 3642 m³ of water remaining confined within the channel. For each observed 1 m² increase in channel area between 1998 and 2014, SS flux to floodplain storage was observed to decrease by 77 Mg, and flux of TP was observed to decrease by 0.05 Mg. If instead of being diverted into floodplain storage, 100% of these SS and TP masses were exported from the watershed with streamflow, each 1 m² increase in channel area would increase watershed export of SS by 77 Mg, and watershed export of TP by 0.05 Mg. At the observed rate of channel enlargement (0.18 m² yr⁻¹), it would take ~5.5 years for the channel cross sectional area to increase by 1 m².

Floodplain trapping efficiency decreased 33% between 1998 and 2014. This may have been primarily driven by the observed decrease in floodplain inundation surface area between years. The method used to estimate floodplain trapping efficiency (Equation 3) is sensitive to areal extent of floodplain inundation (A). In 1998, flows inundated a greater proportion of the floodplain (i.e., larger A) (Figure 3.9) with shallow water, which promoted sediment deposition. During 2014, however, flows lacked the inundation extent seen in 1998 (i.e., smaller A), and an increased proportion of flows (especially for lower discharges) were confined to the channel margin area. These flows were bound between natural levees with no opportunity to spread across the floodplain. While these flows were in fact overbank, their confinement to the channel margin resulted in lesser areal extent and higher velocities (i.e., conditions that reduce sediment settling) than flows observed in 1998.
A number of assumptions were made during this study, many of which may have influenced results. It should be restated that our HEC-RAS models were run under steady flow conditions (i.e., no change in discharge with time). Steady flow conditions are rare in the environment, however, as watersheds are continuously responding to inputs of precipitation and other hydrological factors. Because our models were run under steady flow conditions, we were unable to resolve discharge transients that would likely be important in the floodplain inundation pattern and sequence. While unsteady models driven with observed hydrographs could yield more spatial and temporal detail in overbank flow paths and flow depths, the extent and duration of overbank flows would not be significantly affected, and sediment and P deposition are most strongly influenced by these variables. Furthermore, since our overall objective was to assess change in overbank frequency and volume accompanying channel change, the assumption of steady flow would be expected to have similar results in both 1998 and 2014 models.

We used a single representative suspended sediment grain size to estimate floodplain trapping ability (Equations 3, 4). The relationship between model-estimated floodplain storage and $D_{50}$ was found to vary across a range of grain sizes (2 µm – 250 µm). Floodplain storage sensitivity increased with decreases in $D_{50}$, with the greatest sensitivity observed within the fine silt range (i.e., 2-10 µm). Within the fine silt range, each 1 µm increase in $D_{50}$ resulted in a >100% increase in floodplain storage. For the 20 – 60 µm range, however, each 1 µm increase in $D_{50}$ only increased mass flux by an average of ~5%. As the 20-60 µm range is thought to be a realistic selection range for suspended sediment $D_{50}$, especially for studies such as this, $D_{50}$ should be recognized as having slight to moderate impacts on storage results.
If a finer $D_{50}$ (i.e., <30 µm) were selected, both models would have experienced decreases in SS mass flux to floodplain storage. However, the 2014 model would have seen a disproportionately greater effect, as observed flow characteristics (i.e., propensity of flows to be confined within channel margin and not spread over floodplain) did not promote settling of SS. Spatially, both models would have predicted greater accumulations of SS further (laterally) from the channel margin with a finer $D_{50}$. If a coarser $D_{50}$ were selected (e.g., to more closely mimic the flocculated nature of suspended material), both models would have seen increases in SS mass flux to floodplain storage. For both models, the near channel area would experience increased SS deposition, as the shear zone and steep velocity gradient present in that area promotes settling of large particles. This may lead to the growth of natural levees.

Lastly, we assumed that 100% of stormflow TP occurred as particulate-P, and thus depositional mechanisms of TP would be identical to those of SS. While dissolved P (i.e., orthophosphate) has been documented as being a significant contributor to the annual TP loads of Iowa watersheds (Schilling et al., 2017), we would expect particulate-P to be the dominant contributor to stormflow TP (Gentry et al., 2007), especially during events large enough to produce overbank flow (Sharpley et al., 2008). The assumption of particulate-P dominance in Walnut Creek storm flow is supported by unpublished grab sample data collected at the watershed outlet, where orthophosphate represented, on average, ~19% of storm flow TP. It is not unreasonable to assume that a large proportion of dissolved-P in overbank flow would not be trapped on the floodplain, but instead reenter the channel with flow at points downstream. Thus, if we were to account for dissolved-P contributions to TP, mass flux of TP to floodplain storage would be expected to decrease for both models.
3.4.3 Implications

Previously reported annual loads of SS at the Walnut Creek watershed outlet gauging station (Figure 3.1) have ranged from 2,625 to 16,693 Mg for calendar years 1998 through 2000 (May et al., 1999; Nalley et al., 2000; Nalley et al., 2001; Nalley et al., 2002), and from 6,172 to 25,815 Mg for calendar years 2005 through 2011 (Palmer et al., 2014). Schilling et al. (2006) reported annual loads of TP that ranged from 1.7 to 9.0 Mg for calendar years 2000 – 2005.

As reported in section 3.3.2, the summation of all HEC-RAS discharge profile simulations (i.e., 0.0005 – 0.15 percent exceedance) may act to provide an approximation of hypothetical 1998 and 2014 flow regimes for Walnut Creek. It should be noted that 0.0005 percent exceedance corresponds to the event observed for one hour during the entire data availability period (1995 – 2017). For these regimes, HEC-RAS predicted reductions in overbank floodplain storage totals of 1996 Mg (SS) and 1.41 Mg (TP) between 1998 and 2014. These masses would no longer enter the floodplain storage pool, and would remain confined to the channel, where they may exit the watershed and contribute to watershed SS and TP export. If we consider the maximum reported annual loads of SS (25,815 Mg) and TP (9 Mg), the estimated reduction in export due to change in floodplain storage may increase SS and TP export by ~8 and 16%, respectively. In addition to loss of storage, higher discharges confined to the channel may have greater stream power, resulting in further enhancement of SS and TP export through accelerated bank and bed erosion.

For the main stem of Walnut Creek, streambank erosion contributions to SS loads have been documented for the years 2005 – 2011 (Palmer et al., 2014). Over study duration, streambank erosion contributions of SS ranged from -151 (i.e., accretion on banks) to 9921 Mg yr\(^{-1}\) (mean = 5299 Mg yr\(^{-1}\)). In addition, Beck et al. (2018) estimated streambank
contributions of both SS and TP between May 2015 and May 2017. Streambank erosion contributions of SS were 2900 and 860 Mg for the first and second years, respectively, while contributions of TP were 0.65 and 0.23 Mg, respectively. For most years, annual estimated fluxes of SS and TP to floodplain storage were less than streambank contributions. In many of these years, bank contributions of SS were an order of magnitude greater than the flux to floodplain storage. From these results, it can be assumed that the floodplain along Walnut Creek’s main stem generally acts as a net source of SS and TP to streamflow, and this source will increase further as channel evolution progresses.

The reduction in overbank storage provides a “1-2 punch” for watershed export, as both a storage opportunity is lost and stream power is increased. In addition, the resulting increases to watershed SS and TP export may mask water quality improvements derived from edge-of-field practices aimed at reducing sediment and P delivery to waterways (e.g., no-till practices, riparian buffer strips). This “1-2 punch” may be mitigated to some extent by implementing in-channel practices that act to reduce conveyance and enhance the channel-floodplain connection (e.g., reintroduced meandering, in-channel large wood, increased beaver (Castor canadensis) populations). The authors are aware, however, of the challenges these potential mitigation strategies may present in agricultural regions.

### 3.5 Conclusions

This study combined channel cross section field measurements with HEC-RAS modeling to investigate changes in floodplain inundation and storage within the context of channel geometry change in Walnut Creek, Iowa. Field observations indicate a 16.8% increase in channel cross sectional area over a 16 year period (1998 – 2014). Model results suggest that the increase in channel cross sectional area was associated with increases in
overbank discharge thresholds (i.e., discharges required to force flow to exit channel and enter floodplain), significant decreases in annual floodplain inundation volume and areal extent, as well as decreases in annual flux of SS and TP to floodplain storage of ~24 and ~26%, respectively.

The modeled reduction in floodplain storage potential with a growing channel cross section may have significant implications on SS and TP loads exiting the Walnut Creek watershed. Hypothetical flow regime simulations for 1998 and 2014 indicate that reductions in floodplain storage may represent an apparent increased contribution to SS and TP watershed export of ~8 – 16%, respectively. In addition, reduction in floodplain inundation results in a greater volume of water confined to the channel during flow events. The resulting increase in stream power may accelerate bed and bank erosion, further contributing to SS and TP export.

Cross section data (e.g., dimensional change, bank angles) and field observation of processes (i.e., mass wasting) indicate that the main stem of Walnut Creek is predominately in stage IV (i.e., degradation and widening) of channel evolution. Thus, the degree and frequency of floodplain inundation, as well as flux of SS and TP to floodplain storage are expected to decrease further as the channel continues to degrade and widen in progression towards stages V and VI. Contributions to watershed loads from loss of floodplain storage opportunities, and potentially increased bed and bank contributions from increased stream power, may mask SS and TP reductions achieved through edge of field practices. Because of these factors, it is critical that stage and progression of channel evolution be taken into consideration when addressing sediment and phosphorus loading at the watershed scale.
3.6 Acknowledgements

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3.7 References


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3.8 Figures, Tables, and Photos

Figure 3.1. Location of watershed, monitored channel length, and channel cross section transects, Walnut Creek, Iowa, USA.
Figure 3.2. Channel cross section dimensional change between 1998 and 2014 at a subset of study cross sections. Subset represents typical pattern of degradation and widening along main stem of Walnut Creek, Iowa. Left top banks (looking downstream) located at 0.0 m depth on Y axes.

Figure 3.3. Percent area change for individual channel cross sections between 1998 and 2014, Walnut Creek, Iowa.
Figure 3.4. Flow duration curves derived from watershed outlet mean hourly discharge data, Walnut Creek, Iowa. Black line represents curve for full data availability period, lines in color represent curves for ~5-year periods. Upper portions of curves at left.

Figure 3.5. Floodplain inundation extent and depth for the 1998 (left image) and 2014 (right image) models for the identical watershed outlet discharge of 27.75 m$^3$ s$^{-1}$. The depicted sub-reach is representative of the overall trend of decrease in channel-floodplain connectivity between 1998 and 2014. Blue gradient bar indicates flow depth.
Figure 3.6. Proportion of channel cross sections exhibiting overbank flow in 1998 and 2014, by watershed outlet discharge, Walnut Creek, Iowa.

Figure 3.7. Shift in threshold majority discharge percent exceedance between 1998 (green line) and 2014 (red line) on the watershed outlet flow duration curve (black line), Walnut Creek, Iowa.
Figure 3.8. Model-predicted inundation volume (a.) and surface area (b.) by discharge profile for the entire main-stem floodplain of Walnut Creek, Iowa. Individual data points represent results from individual HEC-RAS flow simulations. Mean hourly discharge is at watershed outlet.

Figure 3.9. Proportion of the floodplain experiencing inundation (normalized by floodplain width at cross section), by discharge profile. Difference in lower case letters for individual discharge profiles indicates significant difference at $\alpha = 0.05$. 
Figure 3.10. Model-predicted SS (a.) and TP (b.) storage by discharge profile for the entire main-stem floodplain of Walnut Creek, Iowa. Individual data points represent results from individual HEC-RAS flow simulations. Mean hourly discharge is at watershed outlet.

Table 3.1. HEC-RAS discharge profiles used to quantify floodplain storage, Walnut Creek, Iowa. Data derived from watershed outlet gauging station FDC for years 1995 – 2017.

<table>
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<tr>
<th>HEC-RAS Discharge Profile</th>
<th>Mean Hourly Discharge (m$^3$ s$^{-1}$)</th>
<th>Exceedance Percentage</th>
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Photo 3.1. Representation of the tall, cohesive streambanks and degree of channel incision present along the main stem of Walnut Creek, Iowa.
Photo 3.2. Mass wasting of streambank material, indicative of Stage IV of stream channel evolution, Walnut Creek, Iowa.
CHAPTER 4. SEDIMENT STORAGE WITHIN AN ALLUVIAL STREAM CHANNEL, IOWA, USA

A manuscript prepared for submission to Earth Surface Processes and Landforms

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Abstract

In-channel sediment and phosphorus storage has been recognized as a significant component of respective watershed budgets, a potentially large contributor to watershed loads, and may act to control sediment routing in watersheds. Despite this, in-channel sediment storage is rarely quantified in the field. In this study we quantified in-channel sediment and total phosphorus (TP) storage within 13.5 km of Walnut Creek, a third-order alluvial channel stream in central Iowa, USA. Total sediment storage mass was estimated at 36,554 Mg, stored at ~2.7 Mg per m channel length. TP mass storage was estimated at 9.4 Mg, stored at $7 \times 10^{-4}$ Mg per m channel length. Sinuous reaches exhibited significantly greater sediment storage volume ($p < 0.001$) and mean sediment depth ($p < 0.001$) compared with straight reaches. Total storage mass was divided into seven feature classes based on depositional processes and position within the channel. In both sinuous and straight reaches, the majority (~72%) of total storage mass was represented by colluvial material accumulations at the streambank toe. Loose bed sediment was the second greatest (18%) contributor to total mass, with the remaining feature classes (e.g., bars) representing a combined ~10% of total storage mass. Reach sinuosity exhibited significant positive correlation ($p = 0.03$) with total reach storage mass, and proved to be the most effective predictor of storage. Total sediment storage mass was ~3.25 times greater than the watershed suspended sediment load for 2015. TP mass was found to be nearly equal to the respective
watershed load for 2015. Both sediment and TP storage masses were ~12.6 times greater than respective streambank erosion mass contributions for 2015. In-channel sediment and TP storage represent significant components of respective Walnut Creek budgets, and may have implications for export of both at the watershed scale.

4.1 Introduction

Sediment storage within stream channels has been recognized as a significant component of watershed sediment budgets (Lambert and Walling, 1988), a potentially large contributor to watershed suspended sediment loads (Collins and Walling, 2007; Walling et al., 1998), and a control on sediment routing within watersheds (Walling and Amos, 1999; Smith and Dragovich, 2008). Quantity and characteristics (i.e., grain size distribution) of stored sediment may have negative implications for aquatic biota habitat (Bilotta and Brazier, 2008), influence processes within the hyporheic zone (Findlay, 1995), and may be associated with contaminants such as heavy metals (Owens et al., 2005). An especially important sediment association in the Midwestern United States is phosphorus (P) (Sharpley et al., 2013). In-channel sediment storage has potential to act as a significant source or sink of dissolved P to streamflow through processes such as adsorption / desorption, and these processes may vary considerably depending on stream physiochemical conditions and inherent properties of stored sediment (Hongthanat et al., 2016; Rahutomo et al., 2018).

Despite the importance of in-channel sediment and P storage to watershed processes, quantification at the watershed scale is rare. Quantification of in-channel sediment presents a series of challenges, notably the exceptionally high spatial and temporal variability (Heitmuller and Hudson, 2009; Walling et al., 2002), and laborious field sampling needed to address this variability (Lambert and Walling, 1988). Of the studies that do exist, the vast majority examine larger, relatively undisturbed watersheds in the UK and Europe (Owens et
Studies from the U.S. typically occur in mountainous regions and focus on the impacts of large-wood on storage (Nakamura, 1993; Ryan et al., 2014), or impacts of sediment storage on fish habitat (May and Lee, 2004). In-channel storage quantification in the Midwest, and especially in watersheds undergoing geomorphic adjustment in response to historic landscape-scale disturbances (e.g., hydrologic alteration, stream straightening) are exceptionally rare.

In this study we seek to quantify and characterize in-channel storage of sediment and P within Walnut Creek, a third-order, alluvial stream draining a ~5200 ha agricultural watershed in central Iowa, USA. Specific study objectives include: 1) estimate in-channel sediment and total phosphorus (TP) storage mass within 13.5 km of stream, 2) estimate distribution of storage among depositional features, 3) characterize the physical and chemical nature of stored sediment, and 4) assess the implications of in-channel storage on sediment and TP loading at the watershed scale. We hypothesize that in-channel sediment and TP storage masses may contribute a significant percentage of watershed suspended sediment and total phosphorus export, and that distribution and characterization of stored sediment will be influenced by channel characteristics and condition, notably channel sinuosity and stream power. In-channel opportunities for sediment storage may be limited due to the current stage of channel evolution and flashy stream hydrology.

4.2 Methods

4.2.1 Watershed Description

Walnut Creek is a perennial, third order stream draining 5218 ha in Jasper County, Iowa, USA (Figure 4.1). The Walnut Creek watershed is located in the Rolling Loess Prairies Level IV Ecoregion (47f), a region typified by rolling topography and well-developed drainage systems (Griffith et al., 1994). Walnut Creek is located within a humid, continental
region with average annual precipitation of approximately 750 mm. Watershed land use consists of 54% rowcrop agriculture (primarily corn-soybean rotation), 36% grassland, and 4% forest, with the remainder comprising roads, farmsteads, and urban areas (Schilling et al., 2006). Of the grassland area, 25% is recently restored tallgrass prairie established by the U.S. Fish and Wildlife Service (USFWS) as part of the Neal Smith National Wildlife Refuge (NSNWR). Since refuge creation in 1991, large tracts of row crop agricultural land have been converted to native tallgrass prairie.

Watershed soils are primarily silty clay loams, or clays formed in loess or till. The upland surficial geology is comprised of a 1-6 m loess cap overlaying pre-Illinoian glacial till, with Holocene alluvial deposits being comprised primarily of silty clay loams, clay loams, or silt loams (Schilling et al., 2009). A majority of watershed soils exhibit moderate to high erosion potential, with 54% being classified as highly erodible (Schilling and Thompson, 2000).

4.2.2 Channel Characteristics

The Walnut Creek channel is incised more than 3 m into its floodplain and is typified by tall, cohesive (i.e., >15% clay content) streambanks. The effects of historic agricultural-associated practices such as row crop conversion, stream channelization, subsurface drainage, and removal of riparian vegetation (Schilling et al., 2011), have led to a flashy hydrology, with Walnut Creek frequently exhibiting rapid responses to precipitation. Several stages of stream channel evolution have been documented in Walnut Creek (Beck et al., 2018; Schilling and Thompson, 2000), with areas of stage III (degradation), stage IV (degradation and widening), and stage V (aggradation and widening) present (Simon, 1989). Channel geomorphic surveys performed in 2014 indicate stage IV as the most prevalent along Walnut Creek’s main stem, with a reported increase in mean channel cross sectional
area of ~17% between 1998 and 2014 (Schilling and Wolter, 2000, Beck et al., 2018b, in review).

Walnut Creek’s floodplain is comprised of a series of loess-derived Holocene alluvial deposits, collectively known as the DeForest Formation (Bettis, 1990). Three primary members of the DeForest Formation comprise the vertical profile of Walnut Creek’s floodplain and thus its streambanks. The Gunder member occupies the lowest stratigraphic position at depths of 1-3 m (Schilling et al., 2009) and commonly comprises the streambank toe and channel bed. The Gunder has been described as a silt loam with massive structure, and exhibits a greater bulk density (1.6 g cm$^{-3}$) and sand content (28.5% by weight) relative to the other members (Beck et al., 2018a). Gunder critical shear stress (i.e., threshold stress applied by flowing water required to initiate erosion) has been documented as being relatively high, ranging from 10.4 (Layzell and Mandel, 2014) to 34.8 Pa (Beck et al., unpublished hydraulic flume data). In addition, (Thomas et al., 2009) documented the Gunder as having a relatively high mechanical shear strength (i.e., threshold force required for material deformation), ranging from 435 – 711 Pa. Thus, the Gunder possesses an inherent resistance to fluvial erosion. The Roberts Creek member (silty clay loam) overlies the Gunder, and represents the pre-European-American settlement landscape surface (Bettis et al., 1992). The Camp Creek member overlies the Roberts Creek and represents the upper stratigraphic position (i.e., floodplain surface). Camp Creek was deposited during the last ~400 years (Bettis et al., 1992), and is typically referred to as ‘post-European-American settlement alluvium’. Camp Creek is described as a silt loam, and ranges in thickness from 0.6 to 1.8 m (Schilling et al., 2009). Distribution, stratigraphic position, thickness, and inherent soil characteristics (e.g., texture, bulk density) of the Camp Creek, Roberts Creek,
and Gunder members have been documented as being consistent throughout the watershed (Schilling et al., 2009).

Monocultural expanses of reed canary grass (*Phalaris arundinacea*) dominate the current vegetative cover of Walnut Creek’s floodplain. These expanses are frequently interspersed with low-density riparian forest, comprised primarily of Eastern Cottonwood (*Populus deltoides* Bartr.), Silver Maple (*Acer saccharinum* L.), Green Ash (*Fraxinus pennsylvanica* Marsh.), Black Walnut (*Juglans nigra* L.), Hackberry (*Celtis occidentalis* L.), White Mulberry (*Morus alba* L.), and Black Willow (*Salix nigra* Marsh.). Along the outer floodplain fringe, landcover transitions to a mixture of row crop agriculture (i.e., corn-soybean rotation) and re-established native tallgrass prairie with increasing floodplain surface elevation.

### 4.2.3 Field Methods

The in-channel sediment storage survey was conducted over 5 days in May 2015. The survey took place under baseflow conditions, with no significant change in stream discharge between sampling dates. Sampling regime was based upon a series of stream reaches (hereafter referred to as *storage reaches*) randomly selected along 13.5 km of channel (Figure 1). Storage reach design and dimensions were based on Iowa Department of Natural Resources (IDNR) Stream Habitat Evaluation Procedures (IOWA, 2012). Storage reaches were 240 m in length, based on IDNR protocol which suggests a length of 30 times the mean channel width (~8 m). Storage reaches were comprised of 10 transects (hereafter referred to as *storage reach transects*) that spanned the channel perpendicular to stream flow, and were spaced 24 m apart along the channel thalweg. Transect width was equal to the estimated water surface width of a ~1.5 year recurrence interval flow (hereafter referred to as *bankfull width*) at the respective transect location. Thus, individual storage reach transects varied in
width, and were based on channel geometry. It should be noted that *bankfull width*, for this study, does not refer to the width of streamflow at the incipient point of floodplain inundation. The lowest extent of live woody vegetation on streambanks was used as an indicator to determine bankfull width, and thus the start and end points of transects.

A total of 12 storage reaches were surveyed during this study, and were distributed along the channel length based on channel sinuosity. To determine storage reach locations, the entire 13.5 km study length was broken down into individual 240 m reaches. Sinuosity of each reach (i.e., ratio of stream channel length to valley length) was determined and reaches were then placed into either sinuous (i.e., sinuosity > 1.2) or straight (i.e., sinuosity ≤ 1.2) categories (hereafter referred to as *sinuosity classes*). Reaches were then selected at random until ~20% of total channel length was equaled. The final set included 7 sinuous and 5 straight storage reaches. The 7-to-5 ratio was based on the ratio of total sinuous length versus total straight length for the entire 13.5 km study channel.

Surveys were initiated in the field by locating the georeferenced upstream boundary of each storage reach with handheld GPS. From this point, a tape was extended downstream along the thalweg to a distance of 24 m, which indicated the location of the first storage reach transect. Care was taken to prevent disturbing the in-transect sediment when approaching from upstream. A meter tape was then extended across the channel, perpendicular to streamflow, using the lowest extent of live woody vegetation as a guide for the start and end points of the transect.

Measurements were taken at 0.5 m intervals spanning the entire transect width. At each 0.5 m interval (hereafter referred to as *probe points*) sediment depth was determined by pushing a 150 cm long × 1 cm wide metal tile probe downward (vertically) into the sediment
until resistance of the underlying Gunder member was detected. All material above this point (i.e., the top of the Gunder) was determined to be stored sediment, and a depth was recorded (Figure 4.2).

The unique color, structure, and relatively high bulk density of the Gunder made it easily recognizable (Figure 4.2) in comparison to other material, both visually and by feel. The “feel” of detecting the Gunder was calibrated with test probes ~5 m upstream of transects. Once each storage reach transect was complete, the tape was stretched an additional 24 m downstream, and the process repeated.

In addition to sediment depth, the type of sediment (hereafter referred to as storage feature class) was recorded at each probe point. The list of storage feature classes included 1) loose bed sediment, 2) side bar, 3) point bar, 4) mid-channel bar, 5) debris jam, 6) beaver dam, and 7) streambank toe colluvium. Loose bed sediment (LBS) was defined as non-consolidated sediment present on the channel bed but not associated with a particular depositional feature. Side bars (SBAR) were defined as linear, flat-surfaced depositional features attached to the low flow channel margin. Point bars (PBAR) were defined as any deposition of sediment which formed on the inside of a meander bend. Mid-channel bars (MBAR) were defined as depositional features not attached to the low flow channel margin, and were often formed downstream of in-channel obstructions. Debris jam sediment (DJAM) was described as any accumulation of sediment immediately upstream of a debris jam, and most likely caused by the jam. Debris was defined as any form of organic material (e.g., wood, corn stalks), living or dead, connected to the streambank or transported to the current location via stream flow. Beaver dam sediment (BDAM) was defined as any accumulation of sediment immediately upstream of a beaver dam, and most likely caused by the dam. Jams
and dams were not further sub-categorized; however, detailed photos, sketches, and dimensions were recorded for all encountered. Streambank toe colluvium (SBC) was defined as any streambank material that had moved gravitationally to the bank toe region. SBC has been observed to generate from a variety of processes including subaerial (e.g., freeze/thaw activity), block failures, and slumps. As with jams and dams, SBC was not further sub-categorized, but photos and descriptions were recorded. It should be noted that material accumulated at the bank toe may not have been entirely colluvial in nature. While some alluvial material was present in the form of a thin veneer, the total volume was negligible compared to the volume of accumulated colluvial material.

4.2.4 Sediment Collection

During October 2015, samples of all storage feature classes were collected in the field and analyzed for bulk density, texture, wet-aggregate stability (WS), and total phosphorus (TP). Within each storage reach, one individual storage feature (e.g., an individual bar) from each storage feature class recorded in the May survey was selected at random for sampling. Individual storage features were located once again using transect and probe point coordinates recorded during the May survey. The sample extraction procedure was dependent on the consistency and cohesion of individual storage features. Sediments exhibiting some degree of cohesion (e.g., SBAR, SBC), were collected using 7.62 cm × 7.62 cm open-ended bulk density cylinders. Sediment contained within the cylinder was used for bulk density analysis, while spoil material generated during extraction was used for analyses of texture, WS, and TP. Sediments exhibiting a low degree of cohesion (e.g., LBS) were collected using 15 cm length × 5 cm diameter polytubes. Polytubes were inserted into sediment vertically to a depth of 5 cm and removed after securing the base of the tube with a metal spatula. Overlying water within the tube was decanted off, and the sample was removed from the tube
and sealed in a plastic bag. Additional sediment for texture, WS, and TP was collected in the same manner and sealed in a separate bag. When sampling features of large spatial extent or systematic spatial variability (e.g., PBAR), multiple samples were extracted from representative areas, compiled into a single bag, and mixed prior to analyses.

In March 2017, streambed and water surface elevations were recorded by traversing the 13.5 km study length with a staff-mounted Trimble R8s real time kinematic (RTK) global navigation satellite system (GNSS) receiver. Bed and water surface elevations were recorded at ~50 m intervals and used in the calculations of streambed and water surface slopes (m m\(^{-1}\)), as well as stream power (W m\(^{-1}\)). Stream power was calculated using the equation:

\[ \Omega = \rho g Q S \]

where \( \Omega \) is stream power (W m\(^{-1}\)), \( \rho \) is the density of water (1,000 kg m\(^{-3}\)), \( g \) is the gravitational constant (9.8 m s\(^{-2}\)), \( Q \) is discharge (m\(^3\) s\(^{-1}\)), and \( S \) is slope (m m\(^{-1}\)). For each storage reach, specific stream power (W m\(^{-2}\)) was calculated using the equation:

\[ \omega = \frac{\Omega}{W} \]

where \( \omega \) is specific stream power (W m\(^{-2}\)), \( \Omega \) is stream power (W m\(^{-1}\)), and \( W \) is stream width (m). Bankfull width discharge was determined from mean hourly discharge data collected at the watershed outlet stream gauging station (Figure 1), and scaled to individual storage reaches using discharge-drainage area relations (Biedenharn et al., 2000; Linhart et al., 2012).

**4.2.5 Laboratory Analyses**

Cylinder-extracted samples were analyzed for bulk density by drying samples at 105°C for 24 h to determine dry weight. Dry weights of samples were then divided by cylinder volume to calculate bulk density. Polytube-extracted samples were analyzed for bulk
density in the same manner, except that sediment was removed from polytube prior to drying. Dry weights of samples were then divided by polytube volume to calculate bulk density. WS was determined by machine sieving, and textural analysis was performed using the pipette method (Gee and Bauder, 1986). Samples were analyzed for TP using the aqua regia method (McGrath and Cunliffe, 1985).

4.2.6 Quantification of Sediment Storage

For each storage reach transect, sediment cross sectional area $A_t$ was calculated using the equation:

(3) \[ A_t = \sum_{i=1}^{n} d_i p \]

where $d_i$ is sediment depth at probe point $i$, and $p$ is probe point interval (0.5 m). Total reach storage volume $V_R$ ($m^3$) was then calculated using equation:

(4) \[ V_R = \bar{A}_t \times L \]

where $\bar{A}_t$ is the reach mean of transect cross sectional area ($m^2$), and $L$ is reach length (240 m). Since sediment bulk density differs among channel features, sediment volume $V_f$ was also computed for individual channel feature classes using Equations 3-4. Total sediment mass stored within a reach $M_R$ (Mg) was then calculated using equation:

(5) \[ M_R = \left( \sum_{j=1}^{n} V_{f,j} \times \rho_{b,j} \right) \times 0.001 \]

where $V_{f,j}$ is total reach volume in storage feature class $j$ ($m^3$) $\rho_{b,j}$ is bulk density of storage feature class $j$ (kg m$^{-3}$). To facilitate scaling of our measurements to the full study area, total reach mass was converted to mass per unit length, $M_l$ (Mg m$^{-1}$):

(6) \[ M_l = M_R / L \]

Scaling to the full channel length in the study area was done separately for sinuous and straight reaches and summed using the equation:
(7) \[ M_t = (\bar{M}_{l,s} \times L_s) + (\bar{M}_{l,h} \times L_h) \]

where, \( M_t \) is total storage mass in study channel (Mg), \( \bar{M}_{l,s} \) and \( \bar{M}_{l,h} \) are the mean mass storage per unit length for sinuous reaches, respectively, and \( L_s \) and \( L_h \) are the total sinuous (7765 m) and straight (5570 m) lengths of study channel, respectively. For comparison of storage between reaches, mass storage rate per channel bed area \( M_a \) (Mg m\(^{-2}\)) was calculated using equation:

(8) \[ M_a = \frac{M_R}{(\bar{w}_b \times L)} \]

where \( \bar{w}_b \) is the reach mean bankfull width (m).

### 4.2.7 Statistical Methods

Data were checked for normality using the Shapiro-Wilk test. If data were normal, means were compared via two sample t-tests. If data were non-normal, means were compared using a Wilcoxon rank-sum test. Correlations between storage mass and hydrologic and hydraulic factors were determined using the Pearson’s correlation coefficient. All procedures were performed using R v. 3.4.1 (R Core Team, 2017).

### 4.3 Results

#### 4.3.1 Quantification of Storage

Total sediment storage volume (i.e., all storage feature classes combined) within the 13.5 km study channel length was estimated to be 30,205 m\(^3\), which equates to \(~2.2\) m\(^3\) per m channel length. Total sediment storage mass was estimated to be 36,554 Mg, which equates to \(~2.7\) Mg per m channel length, and \(~0.4\) Mg per m\(^2\) channel bed area. Clay-size particles (i.e., < 2 µm) represented \(~17\)% (6215 Mg) of total estimated sediment storage mass, while silt-size particles (i.e., 2 – 63 µm) represented \(~54\)% (19,873 Mg). Wet-stable aggregates of diameter > 0.25 mm represented \(~36\)% total sediment storage mass (13,339 Mg), and those
of diameter > 2 mm represented ~12% (4225 Mg). Total phosphorus (TP) storage within the 13.5 km study channel length was estimated to be 9.4 Mg. The total TP storage mass equates to 0.7 kg per m channel length and 0.1 kg per m$^2$ channel bed area.

Overall mean sediment depth (i.e., all feature classes combined) was 0.33 m (± 0.01). Overall mean depth was significantly greater (p < 0.0001) in sinuous reaches (0.4 m ± 0.01) versus straight reaches (0.28 m ± 0.01). Of storage feature classes, PBAR exhibited the greatest overall mean depth and LBS exhibited the lowest (Table 4.1). Select feature classes, notably LBS and SBC, exhibited significantly greater depth in sinuous reaches versus straight (Table 4.1).

SBC represented ~72% (26,229 Mg) of the total estimated sediment storage mass within the 13.5 km study channel length (Figure 4.3 a.). The total SBC sediment mass equates to ~1.9 Mg per m channel length and ~0.3 Mg per m$^2$ of channel bed area. LBS was the second greatest contributor to total storage (~18%), with an estimated mass of 6,540 Mg. The LBS mass equates to ~0.5 Mg per m channel length and ~0.08 Mg per m$^2$ channel bed area. The remaining five storage feature classes (i.e., SBAR, DJAM, BDAM, PBAR, MBAR) represent the remaining ~10% (3785 Mg) of total estimated sediment storage mass, which equates to ~0.3 Mg per m channel length and ~0.04 Mg per m$^2$ channel bed area. Of this mass, SBAR represented the majority (2,198 Mg). It should be noted that no BDAM sediment was recorded during the survey.

Feature class representation within estimated TP mass storage followed the same trend as that observed for sediment. SBC represented ~67% (6.3 Mg) of the total estimated TP storage mass within the 13.5 km study channel length (Figure 4.3 b.). This mass equates to 0.47 kg TP per m channel length and 0.07 kg TP per m$^2$ channel bed area. LBS was the
second greatest contributor to TP storage mass, representing a total of 2.1 Mg (~22%). Total 
LBS mass equates to 0.16 kg TP per m channel length and 0.024 kg TP per m² channel bed 
area. The remaining five storage feature classes represent ~10% (~1 Mg) of the total 
estimated TP storage mass. Within these five classes, SBAR represented the majority of TP 
storage mass (0.55 Mg).

Total estimated sediment storage volume (i.e., all feature classes combined) within 
sinuous reaches (19,342 m³) was greater than that within straight reaches (10,863 m³). 
Sinuous reaches exhibited significantly greater (p < 0.0001) mean sediment cross sectional 
area (i.e., probe point depth × transect width) (2.49 m² ± 0.1) compared to straight reaches 
(1.89 m² ± 0.1) (Figure 4.4). Sinuous reaches stored 65% (23,770 Mg) of the total estimated 
sediment mass, while straight reaches stored 35% (12,784 Mg). Sinuous reaches represented 
~58% (7765 m) of total study channel length, thus their respective storage equates to ~3.1 
Mg per m channel length. Sinuous reach mean bankfull width was ~6.2 m (± 0.7), which 
resulted in ~0.5 Mg sediment storage per m² channel bed area. Straight reaches represented 
42% (5760 m) of total study channel length, with total storage equating to ~2.2 Mg per m 
channel length. Straight reach mean bankfull width was ~6.9 m (± 0.7), which resulted in 
~0.3 Mg sediment storage per m² channel bed area. Sinuous reaches stored ~66% (6.2 Mg) of 
TP storage mass, which equates to 8.0 × 10⁻⁴ Mg per m channel length, and 1.3 × 10⁻⁴ Mg per 
m² channel bed area. Straight reaches stored ~34% (3.2 Mg) of TP mass, which equates to 6 
× 10⁻⁴ Mg storage per m channel length, and 8 × 10⁻⁵ Mg per m² channel bed area.
SBC represented the majority of sediment storage mass in both sinuous (~68%) and straight (~79%) reaches. The same held for TP, with SBC representing the majority of TP mass in both sinuous (~65%) and straight (~71%) reaches. LBS represented the second greatest sediment mass in both sinuous and straight reaches, representing ~18% within both. LBS represented the second greatest TP mass in both sinuous and straight reaches, storing ~21 and ~25% of total TP mass, respectively. Within sinuous reaches, the remaining five storage feature classes represented ~14% of total sediment storage mass and ~14% of TP mass. Within straight reaches, the remaining four feature classes represented ~4% of total sediment mass and ~4% of total TP mass.

Walnut Creek changes from a second to a third order stream at the upstream gauging station (Figure 4.1). It should be noted that all second order stream length (i.e., above upstream gauging station) was classified as sinuous, and thus all straight reaches were third order and located downstream of the upstream gauge. Third order sinuous reaches stored a greater total sediment volume (11,483 m$^3$) compared to third order straight reaches (10,863 m$^3$). Third order sinuous reaches exhibited a significantly greater (p <0.0001) mean sediment cross sectional area (2.6 m$^2$ ± 0.12) compared to third order straight reaches (1.89 m$^2$ ± 0.1). Third order sinuous reaches stored ~2.6 m$^3$ of total sediment volume per m of channel length versus ~1.9 m$^3$ for straight reaches. Sinuous reach volume represented 14,025 Mg of total sediment mass, stored at ~3.2 Mg per m channel length and 0.46 Mg m$^2$ channel bed area. Thus, even though third order sinuous reaches exhibited less total length (4363 m) than third order straight reaches (5760 m), sinuous reaches stored more sediment mass, mass per m channel length, and mass per m$^2$ channel bed area compared to straight reaches. Mean bankfull width for third order sinuous reaches (7.1 m ± 0.05) was slightly greater than that
for third order straight reaches (6.9 m ± 0.7). This trend held for TP mass as well, with third order sinuous reaches storing a total of ~3.5 Mg TP mass, which equated to 0.8 kg per m channel length, and 0.1 kg per m² channel bed area. As with sediment storage, SBC and LBS represented the vast majority of TP storage mass within both sinuous and straight reaches.

Reach sinuosity proved to be the best predictor of mass storage rate (Mg m⁻²) within reaches. Significant positive correlation existed between reach sinuosity and storage rate for all-order (i.e., second and third order) (ρ = 0.62, p value = 0.03), as well as third order (ρ = 0.68, p value = 0.04) analyses. Channel width/depth ratio proved to be an effective predictor only when SBC was omitted from reach Mg m⁻² calculations. As with sinuosity, a significant positive correlation existed between channel width/depth ratio and storage rate for all-order (ρ = 0.76, p value = 0.02) as well as third order (ρ = 0.77, p value = 0.03) analyses. Specific stream power (W m⁻²), channel bed gradient (m m⁻¹), and channel erosional activity (i.e., change in channel cross sectional area between 1998 and 2014) were consistently poor predictors of storage, regardless of stream order or inclusion of SBC.

4.3.2 Characterization of Storage

Among storage feature classes, mean TP concentrations were found to be greatest for MBAR (345 mg kg⁻¹, ± 122) and lowest for SBC (241 mg kg⁻¹, ± 10) (Figure 4.5). A high degree of variability in TP concentration was observed within all feature classes, however, especially those with relatively lower sample sizes (i.e., MBAR, PBAR, DJAM). SBC exhibited the greatest silt-clay content (81% by mass) and PBAR exhibited the lowest (23% by mass) (Table 4.2). MBAR (1.48 g cm⁻³, ±0.1) and PBAR (1.44 g cm⁻³, ± 0.12) represented the greatest mean bulk densities among feature classes, while LBS represented the lowest (1.16 g cm⁻³, ± 0.06) (Table 4.2). PB had the greatest percent mass of wet-stable aggregates for both >0.25 mm (79%, ± 1.3) and >2 mm (30%, ± 3.9) diameter classes (Table 4.2).
When grouped together and averaged, all non-SBC feature classes (NSBC) (i.e., all feature classes combined, excluding SBC) exhibited a number of significant differences ($p < 0.0001$) compared with SBC, notably for silt-clay content. SBC exhibited a lower bulk density and greater TP concentration versus NSBC, however, differences were not significant (Figure 4.6). No trends were observed regarding sediment parameter differences between straight and sinuous reaches, or between second and third order reaches.

4.4 Discussion

4.4.1 Storage Quantification

Walnut Creek was estimated to store an average of ~2.2 m$^3$ of sediment per m channel length, and ~0.35 m$^3$ per m$^2$ channel bed area. These values equate to mass storage of ~2.7 Mg per m channel length and ~0.4 Mg per m$^2$ channel bed area. LBS sediment storage was estimated at ~484 Mg km$^{-1}$. The estimated storage volume and mass for Walnut Creek are within the upper end of those reported in the literature. In a fourth-order, gravel bed river draining 215 km$^2$ in the Southern Pyrenees (Spain), Buendía et al., (2015) reported bed sediment storage ranging from 1.8 to 31 Mg per km channel length. Storage was found to vary significantly with discharge over the course of a year. Lambert and Walling (1988) reported bed storage of 11.4 Mg km$^{-1}$ in a relatively undisturbed UK lowland catchment, where bed storage represented a minimum percentage (~1.6) of annual suspended sediment load. Walling et al. (1998) estimated fine sediment (<150 μm) storage within the gravel-bed Ouse River catchment (UK) to range from 3 to 204 Mg km$^{-1}$, with an overall equivalence of 9-10% of annual suspended sediment load. Owens et al. (1999) estimated 0.56 kg m$^{-2}$ of fine sediment (<150 μm) channel bed storage within a gravel bed UK river (4390 km$^2$ drainage), representing ~4% of the annual suspended sediment load. Walling and Amos (1999) estimated 10 Mg km$^{-1}$ of channel bed storage in a 63.5 km$^2$ agricultural catchment (UK).
experiencing agricultural intensification. In a smaller yet agricultural UK catchment (<4km²), Walling et al. (2002) estimated that channel bed sediment storage represented 0.8 – 2% of annual catchment suspended sediment load. Within the upper range of European estimates, Marttila and Kløve (2014) reported channel bed sediment storage rates in an intensively managed 400 km² Finnish catchment ranging from 8.3 – 127 Mg km⁻¹. Within this catchment, bed storage was estimated to represent 52% of annual suspended sediment load. Collins and Walling (2007a, 2007b) reported similarly high contributions to suspended sediment loads (18-57%) from a series of UK catchments ranging in size from 183 – 437 km².

The majority of European studies examined bed sediment exclusively (similar to the LBS storage feature class), and used the bed-agitation technique described by Lambert and Walling (1988). This method quantifies the upper ~10 cm of channel bed sediment, thus results should be examined under that context. The LBS storage values reported from Walnut Creek, even if only considering the mass represented in the upper 10 cm, were still greater than those present in the European studies. Most European studies represented catchments much larger than Walnut Creek, may have had less recent, and less intense landscape disturbance, exhibited less flashy hydrology, were gravel bed, and reported lower mean catchment suspended sediment concentrations than the current study. Storage values in the Midwestern United States, though rare, more closely resemble those estimated for Walnut Creek. Lamba et al. (2015) estimated in-channel sediment storage in a series of Wisconsin catchments to range from 54 – 394 Mg km⁻¹. The catchment that more closely resembled the size of Walnut Creek (~52 km²) was reported to have the lowest storage rate (54 Mg km⁻¹), however.
Most of the sediment and TP storage mass within Walnut Creek was represented by SBC. Subaerial erosion and mass wasting processes have been reported as significant streambank recession processes in Walnut Creek (Beck et al., 2018a). These processes may result in large accumulations of colluvium to amass at the bank toe region, especially during late winter and early spring (Couper and Maddock, 2001; Hooke, 1979). Depending on the magnitude of subsequent flow events, this material may then be partially or entirely removed by fluvial erosion. Compared to other storage feature classes, SBC was relatively ubiquitous, and evenly distributed along the channel length, although in varying degrees of activity. The second largest feature class to contribute to total sediment and TP storage was LBS. As with SBC, LBS was ubiquitous and relatively evenly distributed along the channel, and thus was recorded in nearly every storage reach transect. The combination of remaining storage features (i.e., SBAR, DJAM, PBAR, MBAR) represented a relatively minor proportion (~10%) of total estimated sediment and TP storage. Although these features were not as ubiquitous as SBC and LBS, based on field observations, their contributions to total storage may have been underestimated as a result of survey design. Individual storage features, such as bars, that were intercepted by storage transects were relatively small in areal extent (i.e., < 24 m). Thus, a number of these features, though observed, fell between the 24 m spacing of transects and were not recorded in the survey. However, it is believed that because the survey covered 20% of the total study channel length, enough individual features were intercepted by transects to represent an accurate estimate of storage.

BDAM storage was not detected at all in the survey, and only one dam was observed over the entire 2015 field season. It is believed, however, that BDAM has potential to be a significant, albeit transient, source of storage within Walnut Creek (Gurnell, 1998; Pollock,
2007). For example, low stream discharge during 2016 and 2017 resulted in the construction of a number of substantial dams (i.e., dams capable of producing noticeable changes in water surface elevation and velocity) within three reaches of Walnut Creek’s main stem, as well as within a major tributary. These dams resulted in significant accumulations of sediment within associated reaches, with greatest accumulations immediately upstream of structures.

The majority of sediment and TP storage occurred within sinuous reaches (i.e., sinuosity > 1.2). Sinuous reaches exhibited greater sediment volume, sediment and TP mass storage, as well as significantly greater mean sediment depth compared to straight reaches. In addition, all individual feature classes exhibited greater sediment and TP mass storage within sinuous reaches versus straight reaches. Reaches with greater sinuosity would be expected to promote sediment deposition through reduced slopes and flow velocities, as well as increased energy dissipation along banks, all leading to reductions in sediment transport capacity. In addition, sinuous reaches contain deposition features inherently absent from straight reaches. Most notable is PBAR, the feature class which exhibited the greatest mean sediment depth.

In addition to hydraulics, riparian land cover may partially explain the higher storage rates exhibited by sinuous reaches. Riparian land cover for straight reaches in this study was primarily cool season grass, with scattered lone trees and/or single rows of trees lining streambanks. Sinuous reach riparian areas, especially third order reaches, exhibited greater storage. Sinuous reaches, especially those of third order, were often bordered by riparian forest comprised of short-lived, weak-wooded trees such as Silver maple and Boxelder. Field observations indicate greater recruitment of woody material to the channel and floodplain within sinuous reaches. The greater amount of in-stream wood (both jams and single pieces) observed within sinuous reaches may have contributed to reduced flow velocities and a
general decrease of channel conveyance within the reach, further promoting sediment deposition (Nakamura and Swanson, 1993; Ryan et al., 2014).

Clay sized particles were found to represent ~17% of total storage mass, while silt size particles represented ~54% of total storage mass. It should be restated that grain size was determined by the pipette method, and thus represents ultimate grain size (i.e., dispersed). This may not represent the true flocculated nature of in-channel sediment, however (Thonon et al., 2005). Wet-stable aggregate data may provide a more accurate description of the particle diameters present in stored material. Wet-stable aggregates >0.25 mm diameter were found to represent ~48% of total storage mass. Storage features subjected to continuous in-stream flow and mixing (i.e., NSBC) exhibited a significantly greater proportion (% mass) of > 0.25 mm wet-stable aggregates than SBC. Since aggregates most likely do not form in-channel (i.e., area of high mixing), and in fact may be expected to degrade in-channel due to attrition, it may be assumed that bank material (SBC) contributes a significant mass to NSBC channel storage. The greater proportion (% mass) of > 0.25 mm aggregates present in NSBC may be a result of the removal of fines by streamflow.

4.4.2 Predictors of Storage

Reach sinuosity was found to exhibit a significant positive correlation with total sediment mass storage. Width/depth ratio also exhibited a significant positive correlation with storage, however, only when SBC data were omitted from analyses. Reaches with larger width/depth ratios would be expected to exhibit larger hydraulic radii (flow cross sectional area divided by wetted perimeter), typified by a wider channel bed. A wide channel bed would result in a greater percentage of flow in contact with channel boundaries, thus increasing the amount of energy required to overcome boundary resistance, decreasing conveyance, and promoting sediment deposition.
Streambed gradient and specific stream power (Equation 2) were found to correlate poorly with mass storage. This was unexpected, as transport capacity relies heavily on these factors and strong correlation between sediment storage and stream power has been documented (Naden et al., 2016). However, the poor correlation may have been influenced by in-field gradient measurement. Overall channel bed gradient of the 13.5 km study channel was relatively low in general (0.0017 m m\(^{-1}\)), and field-measurements of gradient exhibited high variability between reaches. This variability may have been due in part to precision of GPS survey equipment, and bed topography influences on survey rod position. Because the equation used to calculate stream power (Equation 2) is sensitive to gradient, slight in-field differences in rod placement may have resulted in large differences in power. In addition, the study length only spanned 13.5 km, which may not be an adequate length for presence of significant reach scale gradient differences which may affect storage. Given longer channel length (orders of magnitude), differences based on gradient may appear, for example in larger watersheds where zones of sediment production, transfer and accumulation are distinct. Sinuous reaches would be expected to have lower gradient versus straight reaches, and may have had in this study, but this trend may have been masked by field measurement issues.

Change in cross sectional area was also found correlate poorly with storage mass. Change in cross sectional area represents channel dimensional change over a 16 year period (Beck et al., 2018b) and was utilized as a proxy for investigating the relationship between streambank erosion and channel storage. It may be expected that reaches with greater streambank contribution would exhibit greater storage (Smith and Dragovich, 2008). However, because Walnut Creek is currently in stage IV of channel evolution (i.e., the
majority of channel is experiencing degradation and widening) (Beck et al., 2018b.)
aggradation, in general, may be limited, and the bulk of streambank contributions would be
expected to be transported from the reach with streamflow. Channel change may correlate
better as channel evolution progresses through stages V (aggradation and widening) and VI
(quasi-equilibrium).

4.4.3 Characterization

SBC exhibited relative low variability for all characteristics across at the watershed scale, which reflects the reported consistency in streambank alluvial stratigraphy and sediment characteristics reported by Schilling et al., 2009. A high degree of variability was present, however, for all sediment characteristics exhibited by the remaining feature classes (NSBC). The high variability may be expected from NSBC, under the influence of in-channel mixing and flow dynamics, and the high variability of depositional conditions, hydraulics, and zones within the channel (Heitmuller and Hudson, 2009). Even though no significant difference was detected, SBC exhibited a lower TP concentration, and less variability in concentration, than that of NSBC. This difference may imply absorption of streamflow dissolved P to NSBC sediments (McDaniel et al., 2009). Another notable difference was that SBC exhibited nearly double the silt-clay content of NSBC. This significant difference was most likely due to the removal of fines by streamflow.

4.4.4 Implications

The total survey-estimated sediment storage mass (36,554 Mg) was ~3.25 times greater than the 2015 suspended sediment load of Walnut Creek (11,203 Mg). Previously reported annual suspended sediment loads for Walnut Creek range from 2,625 to 25,815 Mg (Nalley et al., 2000; Nalley et al., 2001; Palmer et al., 2014). Across this range, the 2015 estimated sediment storage mass represents the equivalent of ~43% of the maximum reported
annual suspended sediment load and ~4.3 times greater than the minimum reported load. The feature class representing the greatest storage mass, SBC, was estimated to be ~2.3 times greater than the 2015 suspended sediment load. Estimated SBC storage mass was greater than any previously reported annual load of suspended sediment, and nearly ~10 times greater than the minimum reported annual load. The total survey-estimated TP storage mass (9.4 Mg) was approximately equal to the 2015 TP load for Walnut Creek (9.5 Mg). The estimated 2015 TP storage mass was greater than annual TP loads reported by Schilling et al. (2006) for the years 2000 - 2005 (1.7 – 9.0 Mg). SBC contained the equivalent of ~66% of the 2015 load, and would represent a mass ~3.7 times greater than the minimum annual load reported by Schilling et al. (2006).

Estimated LBS sediment storage and TP masses were equivalent to ~58% and ~22% of respective 2015 watershed loads. LBS sediment storage volume was estimated in 1998 for the third-order length of Walnut Creek (Schilling and Wolter, 2000). Researchers used a similar probe-depth method and focused exclusively on LBS within the third order length of Walnut Creek. The estimate of LBS storage volume for the 1998 survey (0.58 m$^3$ m$^{-1}$) was strikingly similar to the current survey estimate (0.48 m$^3$ m$^{-1}$). This similarity may suggest no net change in in-channel storage over the 17 year span. Increased storage (i.e., aggradation) may only occur as the channel progresses through stages V and VI of channel evolution.

Streambank erosion contributions to Walnut Creek suspended sediment and TP loads were estimated at 2900 and 0.65 Mg, respectively, for 2015 (Beck et al., 2018a). Palmer et al (2014) reported a mean annual suspended sediment contribution of ~5300 Mg from Walnut Creek streambanks between 2005 and 2011. For 2015, streambank suspended sediment contributions would equate to ~8% of the estimated sediment storage mass, and ~7% of
estimated TP mass storage. In other words, it would take ~13 years of bank erosion at the rate of 2015 to match in-channel stored sediment and TP mass. Assuming no change in storage over time, the 2015 storage estimate is ~3.5 times greater than the maximum annual streambank contribution estimated by Palmer et al. (2014). It should be noted that Palmer et al. (2014) and Beck et al. (2018a) report bank contributions from main stem only. Additional bank contributions may be sourced from tributaries, and not accounted for in those studies.

Land use, although not a focus of this study, may have played a role in the exceptionally high sediment mass storage within a particular reach. A particular reach exhibited a total sediment storage mass rate of 0.73 Mg m$^{-2}$, which was ~1.8 times the study average. The reach exhibited a LBS storage rate of 0.18 Mg m$^{-2}$, which was ~2.25 times greater than the study average, and a mean LBS depth of 0.35m, ~2.3 times greater than study average. The reach in question was the only storage reach with active cattle grazing occurring within the riparian area. Cattle had full access to the stream channel, and were frequently observed loafing within the stream. In addition to trampled banks, vegetative overhang (i.e., floodplain surface grass draping streambank face below) on vertical streambanks was nearly non-existent due to grazing activity. The lack of vegetative overhang allowed for full exposure of bank faces to freeze / thaw cycles and other subaerial erosional processes, resulting in excessive erosion and colluvial buildup on the bank toe during late winter and early spring in comparison to other study reaches (field observations). These observations are consistent with results reported in the literature regarding cattle impacts to streambanks and riparian areas (Trimble and Mendel, 1995; Tufekcioglu et al., 2013).
4.5 Conclusions

In-channel sediment and TP storage masses within Walnut Creek were found to be significant in comparison to respective annual loads and streambank contributions. Total estimated sediment storage mass within 13.5 km of channel was ~3.25 times greater than the watershed suspended sediment load for 2015. Estimated TP mass storage was approximately equal to the 2015 watershed load. Total estimated sediment and TP storage mass were both found to be ~12.5 times greater than respective streambank contributions for 2015. The estimated sediment mass storage (~2.7 Mg m$^{-1}$) was found to be high relative to other storage values reported in the literature. In addition, the ratio of sediment storage mass to annual watershed load was also relatively high in comparison to other studies, although significant annual variability existed. Thus, in-channel sediment and TP storage may play a significant role in respective watershed routing, loading, and the overall budgets of these parameters. It should be noted, however, that this estimate is a snapshot, and the relationship between sediment storage and overall watershed sediment dynamics may exhibit significant inter-annual variability.

The majority of Walnut Creek’s sediment and TP mass storage occurred within sinuous reaches. Sinuous reaches exhibited significantly greater total sediment storage volume, mass, and depth in comparison to straight reaches. All storage features classes exhibited greater sediment and TP mass storage within sinuous reaches. In addition, sinuosity exhibited the greatest positive correlation with reach storage. In addition to lower velocities and greater energy dissipation due to meandering, in-stream wood may be partially responsible for the increased sediment and TP storage within sinuous reaches. Sinuous reaches, especially those of third-order, frequently dissected stands of riparian forest, and a higher degree of recruitment of woody material to the channel and floodplain was observed.
in these areas compared to straight reaches. Woody material may have acted to not only trap sediment in association with debris jams, but lower the conveyance of the reach in general, lowering streamflow velocity and promoting sediment deposition.

Within both sinuous and straight reaches, the bulk of stored sediment and TP occurred as SBC and LBS, with the remaining storage feature classes combined representing ~10% of total storage. The dominance of SBC may be expected, as the majority of Walnut Creek’s length is within stage IV of stream channel evolution, as indicated by observations of ubiquitous mass wasting and documented channel degradation and widening. These processes result in significant accumulation of transient sediment storage in the streambank toe region. When compared with all other storage features combined (i.e., NSBC), SBC exhibited lower TP concentration compared to the combination of all other storage feature classes (NSBC). This difference may be indicative of P sorption to in-stream sediments once eroded from streambanks, and may emphasize the importance of in-channel storage to in-stream P dynamics.

Estimated volume of sediment storage per m of channel was found to be strikingly similar between the 1998 and 2015 surveys. This seemingly no net change in channel storage may be a result of the stage of channel evolution present within Walnut Creek. A net increase in storage may only occur when Walnut Creek progresses from stage IV (degradation and widening) to stages V (aggradation and widening) and VI (quasi-equilibrium). Increased storage may be promoted, however, through practices that act to reduce the relatively high channel conveyance associated with stage IV of channel evolution. Reintroduction of meanders, promotion of in-stream wood, and increased beaver (*Castor Canadensis*) populations may lead to significant reductions in channel conveyance, a net increase in
channel sediment and TP storage, and potential reductions in overall watershed sediment and TP loads.

4.6 Acknowledgments

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4.8 Figures and Tables

Figure 4.1. Location of watershed, surveyed channel length, and storage reaches, Walnut Creek, Iowa, USA.
Figure 4.2. Example of storage reach transect setup and probe point sediment depth measurement. Inset displays position of sediment storage relative to Gunder. Bankfull width (i.e., start of storage reach transect) denoted as $W_{bf}$.

Figure 4.3. Total sediment storage mass (a.) and total TP storage mass (b.) within the 13.5 km study channel length, Walnut Creek, Iowa.
Figure 4.4. Sediment cross sectional area for individual storage reach transects, by sinuosity class, Walnut Creek, Iowa. Difference in upper case letters indicates significant difference at $\alpha = 0.05$.

Figure 4.5. Storage feature class TP concentrations, Walnut Creek, Iowa.
Figure 4.6. Storage feature class TP concentrations, Walnut Creek, Iowa. Non-SBC features denoted as NSBC. Differences in upper case letters indicate significant difference between feature classes at $\alpha = 0.05$.

Table 4.1. Mean sediment depth of storage feature classes, for overall study channel length and sinuosity class. Significant differences in feature depth by sinuosity class indicated by differences in lower case letters.

<table>
<thead>
<tr>
<th>Feature Class</th>
<th>Overall mean depth (m)</th>
<th>Sinuous reach mean depth (m)</th>
<th>Straight reach mean depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose bed sediment</td>
<td>0.15 ± 0.01</td>
<td>0.18 ± 0.01 (a)</td>
<td>0.12 ± 0.01 (b)</td>
</tr>
<tr>
<td>Streambank toe colluvium</td>
<td>0.51 ± 0.01</td>
<td>0.57 ± 0.02 (a)</td>
<td>0.43 ± 0.01 (b)</td>
</tr>
<tr>
<td>Side bar</td>
<td>0.44 ± 0.03</td>
<td>0.46 ± 0.03 (a)</td>
<td>0.34 ± 0.01 (a)</td>
</tr>
<tr>
<td>Debris jam</td>
<td>0.39 ± 0.04</td>
<td>0.41 ± 0.05 (a)</td>
<td>0.15 ± 0.01 (b)</td>
</tr>
<tr>
<td>Mid-channel bar</td>
<td>0.39 ± 0.09</td>
<td>0.64 ± 0.06 (a)</td>
<td>0.27 ± 0.06 (a)</td>
</tr>
<tr>
<td>Point bar</td>
<td>0.77 ± 0.11</td>
<td>0.77 ± 0.11</td>
<td>na</td>
</tr>
</tbody>
</table>
Table 4.2. Sediment characteristics by feature class, all sinuosity classes and stream orders combined, Walnut Creek, Iowa. Values represent mean values across both sinuosity classes and both stream orders. Wet-stable aggregates denoted by WSA. Mean values for combined LBS, SBAR, DJAM, PBAR, MBAR denoted by Non-streambank toe colluvium. Significant differences ($\alpha = 0.05$) between SBC and NSBC parameters indicated by differing lower case letters.

<table>
<thead>
<tr>
<th>Feature Class</th>
<th>% Silt-clay</th>
<th>% Clay</th>
<th>Bulk Density (g cm$^{-3}$)</th>
<th>WSA &gt; 0.25 mm (% mass)</th>
<th>WSA &gt; 2 mm (% mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streambank toe colluvium</td>
<td>81 ± 2 (a)</td>
<td>18 ± 0.5 (a)</td>
<td>1.2 ± 0.02 (a)</td>
<td>31 ± 4 (a)</td>
<td>12 ± 3 (a)</td>
</tr>
<tr>
<td>Non-streambank toe colluvium</td>
<td>48 ± 4 (b)</td>
<td>13 ± 1 (b)</td>
<td>1.28 ± 0.04 (a)</td>
<td>49 ± 4 (b)</td>
<td>10 ± 2 (a)</td>
</tr>
<tr>
<td>Loose bed sediment</td>
<td>44 ± 6</td>
<td>14 ± 2</td>
<td>1.16 ± 0.06</td>
<td>51 ± 4</td>
<td>11 ± 2</td>
</tr>
<tr>
<td>Side bar</td>
<td>64 ± 8</td>
<td>15 ± 3</td>
<td>1.34 ± 0.05</td>
<td>41 ± 7</td>
<td>6 ± 2</td>
</tr>
<tr>
<td>Debris jam</td>
<td>47 ± 12</td>
<td>13 ± 2</td>
<td>1.33 ± 0.06</td>
<td>45 ± 17</td>
<td>1 ± 0.4</td>
</tr>
<tr>
<td>Point bar</td>
<td>23 ± 8</td>
<td>6 ± 3</td>
<td>1.44 ± 0.12</td>
<td>79 ± 1</td>
<td>30 ± 4</td>
</tr>
<tr>
<td>Mid-channel bar</td>
<td>42 ± 14</td>
<td>9 ± 5</td>
<td>1.47 ± 0.1</td>
<td>42 ± 28</td>
<td>6 ± 5</td>
</tr>
</tbody>
</table>
CHAPTER 5. CONCLUSIONS

5.1 Streambank Erosion

Streambank recession rates during the study period were low (6.3 – 12.3 cm yr\(^{-1}\)) relative to rates previously reported for Walnut Creek. Streambank contributions were estimated to represent between 4.0 and 43.9\% of historic reported annual suspended sediment (SS) loads, and between 2.7 and 37.5\% of reported total phosphorus (TP) loads, and while relatively low, these estimated contributions did fall within the range reported in a number of Midwestern studies. The majority of the streambank mass contributions were represented by weathered / colluvial material (i.e., non-member material) originating from Walnut Creek’s primary floodplain alluvial members. This material was detached or prepared for detachment from bank faces by subaerial processes (e.g., freeze-thaw, wet-dry cycles) or mass wasting, was commonly amassed at the mid-bank to bank toe region, and was found to represent a majority percentage of streambank face surface area. This material exhibited relatively lower cohesion and bulk density compared with the original source members, and exhibited greater susceptibility to removal by fluvial erosion versus its source members. Thus, it may be concluded that the processes of subaerial preparation / weathering and mass wasting are primary drivers of streambank retreat in Walnut Creek, holding greater significance than the fluvial erosional forces exhibited by streamflow. It should be noted that while the alluvial members that comprise Walnut Creek’s streambanks (i.e., Camp Creek, Roberts Creek, Gunder) represented a minor contribution to streambank mass losses, more research is needed as to the proportional impact these specific materials will have on in-stream P dynamics once eroded.
The streambank recession rates observed between 2014 and 2017 are believed to be a result of relatively low annual stream discharges and a low prevalence of large stormflow events. Over the course of the study, many streambanks previously identified in the 2013 eroding length survey as “severely” or “very severely” eroding were observed to be undergoing a healing process. Reduced streamflow between 2014 and 2017 allowed for colluvial material to amass at bank toe regions, reducing bank angles and allowing for the establishment of vegetation. It is believed that vegetation not only acted to increase soil cohesion through rooting, but also promoted alluvial deposition on banks and reduced subaerial erosion by insulating bank soils from temperature extremes. The effect that bank vegetation had on reducing subaerial erosion was most pronounced in the grazed reaches of the study. Here, lack of vegetation both on and overhanging streambank faces (i.e, grass on floodplain surface draping upper bank regions), due to grazing activity, contributed to excessive subaerial erosion-generated sediment accumulations at the bank toe, especially during late winter and early spring. These observations are supported by pin data as well as in-channel sediment storage data, as the actively grazed reaches exhibited nearly double the in-channel sediment storage mass as non-grazed reaches. The fact that many banks appeared to heal over the study duration suggests that watershed scale streambank erosion may have been underestimated. Field observations and previous studies indicate that locations of streambank erosion are highly variable both spatially and temporally. At the same time that specific banks were healing, other bank erosion locations were observed to emerge. This may be expected, as without a decrease in streamflow power, reduced sediment supply from healing banks may result in new areas of erosion. Continuing to measure streambank pins on healing banks, and extrapolating this estimate to the watershed scale, may have
underestimated the true nature of erosion during the study. Thus, it is recommended that regular surveys of streambank eroding length be conducted when attempting to estimate streambank erosion at the watershed scale. Although bank erosion locations were observed to be highly variable both spatially and temporally, a number streambanks included in the study set were found to perpetually exhibit severe erosion. The severe nature of erosion within this subset can be observed in the data collected by previous graduate students as well, suggesting that these banks have exhibited severe erosion since at least 2005. Groundwater seeps were observed to occur at a majority of these banks, often at the interface of the Roberts Creek and Gunder members, and may have been a factor in their perpetual eroding condition. Seeps act to saturate bank soil and reduce its cohesion. This reduction in cohesion promotes bank failures / slumps and leaves soil more susceptible to fluvial erosion. Streambanks located within actively grazed reaches also exhibited long term trends of severe erosion, which are believed to be caused, in part, by the subaerial processes previously discussed.

Stream erosion along tributaries are believe to be a significant contributor to Walnut Creek SS and TP loads. At the same time that a number of main stem streambanks were observed to be healing, a number of major tributaries, especially in the southern area of the watershed, were observed to exhibit vertical, severely eroding banks that lacked vegetative cover. In addition, deep accumulations of sediment were observed on the beds of tributaries, as well as main stem channel reaches immediately downstream of tributary confluences. These field observations were supported by 2017 eroding length survey data, where significant percentages of tributary streambank lengths were classified as severely or very severely eroding. It is believed that tributaries are currently downcutting in order to achieve the bed elevation of Walnut Creek’s main stem.
5.2 Floodplain Access and Storage

Nearly 20 years of channel cross section data indicate a clear pattern of degradation and widening along a majority of Walnut Creek’s main stem. This pattern is indicative of stage IV of stream channel evolution. The associated increase in channel conveyance is believed to have led to a decrease in connectivity between Walnut Creek and its floodplain. Hydraulic simulation results suggest that overbank discharge thresholds (i.e., channel discharge required to force streamflow to exit the channel and inundate the floodplain) have increased 13 to 28% between 1998 and 2014. In other words, Walnut Creek now requires streamflow events of greater magnitude in order to inundate its floodplain than it did in 1998. The decrease in floodplain access is estimated to have reduced annual flux of SS and TP to floodplain storage by 24 and 26%, respectively. These lost storage opportunities have been estimated to increase watershed export of SS and TP by 8 and 16%, respectively. In addition, reduction in floodplain inundation results in a greater volume of water confined to the channel during flow events. The resulting increase in stream power may accelerate bed and bank erosion, further contributing to SS and TP export. This “1-2 punch” of lost storage and increased stream power may act to mask SS and TP reductions achieved through upland, edge-of-field best management practices.

Overall, estimated annual mass fluxes of SS and TP to Walnut Creek’s floodplain are less than respective streambank contributions to SS and TP export. Thus, it can be assumed that the floodplain acts as a net source of SS and TP to streamflow in Walnut Creek. This trend is expected to remain in place until Walnut Creek progresses to stages V (aggradation and widening) and VI (quasi-equilibrium) of stream channel evolution, at which point opportunities for floodplain-channel connectivity and storage of SS and TP on the floodplain may increase. Thus, it is critical that stage and progression of stream channel evolution be
taken into consideration when addressing sediment and phosphorus loading at the watershed scale.

### 5.3 In-Channel Storage

Masses of in-channel SS and TP storage were found to be significant in comparison to respective annual streambank erosion contributions and watershed loads. Estimated sediment storage values are incredibly high compared to other, mostly European, studies. The European studies were conducted in larger watersheds that do not appear to be experiencing the degree of channel degradation and widening exhibited in Walnut Creek. Also, nearly all streams were gravel-bed, exhibited a greater degree of channel-floodplain connectivity (i.e., floodplain storage was a more significant component of sediment budget), less flashy hydrology, and lacked the degree of watershed disturbance and time since major watershed disturbance as those of Walnut Creek. Studies from Midwestern U.S. watersheds with similar land use and disturbance histories, however, more closely matched sediment storage estimates for Walnut Creek.

Sinuous reaches were estimated to store the majority of Walnut Creek’s sediment and TP. Sinuous reaches had significantly greater storage volumes and sediment depths compared to straight reaches, and stored greater masses of both sediment and TP. Sinuosity exhibited a significant positive correlation with storage mass, and was the most effective predictor of storage. In-stream wood may have contributed to increased storage mass within sinuous reaches, to an extent. Although debris jams were documented within both sinuous and straight reaches, greater recruitment of woody material to the channel and floodplain was observed in sinuous reaches. Sinuous reaches were typically associated with forested riparian areas, while the riparian vegetation of straight reaches was typically grass or single rows of streambank trees. In-channel wood may, in addition to trapping sediment associated with
jams, reduce the overall conveyance of the reach, thus reducing velocities and promoting sediment deposition. In addition, beaver dams, while not documented in survey and rarely observed during the 2015 field season, have potential to be a significant contributor to in-channel storage. This storage may be both directly associated with dams and within the entire reach in general. When the lone dam observed over the 2015 field season was breached during a near-out-of-bank flow event in 2015, sediment deposits on the bed and channel margins resulting from that jam were exposed, and significant accumulations of sediment were observed for a distance +100 m upstream of the dam. Beaver dam storage, although potentially significant, may be transient in the context of Walnut Creek’s dam-busting flashy hydrology.

The vast majority (>70%) of Walnut Creek’s in-channel storage was represented by streambank toe colluvium (SBC). This importance of colluvial material to sediment dynamics within Walnut Creek is supported by streambank-face surface area surveys and streambank erosion data. The importance of SBC is expected to be maintained as the channel of Walnut Creek continues to degrade and widen in association with stage IV of stream channel evolution. Loose bed sediment (LBS) represented the second greatest contributor to total in-channel storage (18%), while the remaining storage feature classes combined to represent a mere 10%. A number of notable differences occurred between SBC and the remaining storage feature classes (i.e., those features present within the zone of active fluvial mixing, collectively referred to as NSBC). Notably, NSBC had a higher TP concentration, which may be a result of adsorption of dissolved streamflow P to in-channel sediments. In addition, NSBC exhibited a significantly higher percentage (by mass) of >0.25 mm wet-stable aggregates, and nearly one-half the silt-clay content of SBC. These differences most
likely resulted from removal of fines by streamflow. The significant proportion of >0.25 mm aggregates within NSBC mass, however, may indicate that streambank material is a significant contributor to total in-channel storage. The majority of aggregates observed during the wet-sieving process (as well as in the field) exhibited a smooth, almost polished, surface. This smoothed appearance is presumably a result of aggregates entering the channel via streambank erosion, then smoothening by rolling, sliding or saltation along the channel bed over time. As an example, many of the aggregates appeared to have the same red color and texture as the iron concretions commonly observed in streambank Gunder material.

Lastly, surveys indicate no net change in LBS storage between 1998 and 2014. No change over the 16 year period may be further evidence that bed aggradation (i.e., net gain in storage) will not occur until Walnut Creek has progressed into stages V and VI of stream channel evolution.

### 5.4 Management Implications

Walnut Creek’s degradation and widening will continue to contribute significant masses of SS and TP to streamflow until channel dimension, pattern and profile adjust to the point where they are in quasi-equilibrium with the altered hydrological regime. This is expected to occur naturally, over time, as channel evolution progresses towards stages V and VI. However, the natural progression may be regulated by the Gunder member, as it acts as a relatively erosion-resistant base that slows bed degradation and thus widening. Rehabilitation of hydrology to a more natural state (i.e., less flashy) is critical in order to reduce bank erosion, increase channel-floodplain connectivity, increase in-channel storage, and work to reduce in-channel legacy source contributions to watershed SS and TP loads.

In addition to in-field practices aimed at mitigating stream flashiness (e.g., constructed wetlands), in-channel practices may be needed to reduce channel conveyance and reduce
stream power, thus helping to stabilize banks and promote sediment deposition and storage. In other words, we may need to speed up Walnut Creek’s progression to stages V and VI of channel evolution. Reintroduced meandering will act to increase stream energy dissipation, and promote net deposition through reduced streamflow velocities. It is recognized that reintroduced meanders will increase sediment contributions at specific locations, however, the overall reduction in overall channel velocity would be expected to produce a net reduction in sediment export. Promotion of in-stream wood and beaver activity would also act to reduce channel conveyance and promote sediment storage and bed aggradation. Bed aggradation will promote channel-floodplain connectivity, and perhaps return the floodplain to a net sediment and TP sink. Reductions in flow velocities and stream flashiness resulting from these practices may provide streambanks ample time to revegetate, thus increasing resistance to fluvial and subaerial erosion. Until Walnut Creek’s flashy hydrology is addressed, upland progress to reduce delivery of sediment and TP to the channel may be masked by increased contributions from in-channel sources.