FLOODPLAIN SEDIMENT DEPOSITION IN NORTHERN CALIFORNIA, USA

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Abstract
Land use changes have occurred in the Stemple Creek watershed in northern California USA that have increased and then decreased the erosion and movement of soil from agricultural land to floodplain, stream channels, and the Bodega Bay. This study documented sediment deposition rates and patterns in the floodplain of Stemple Creek. Deposition rates ranged from 0.31 to 3.50 cm yr^{-1} with an average of 1.29 ∀ 1.04 cm yr^{-1} for the 1954 to 1964 period and from 0.26 to 1.84 cm yr^{-1} with an average of 0.85 ∀ 0.41 cm yr^{-1} for the period from 1964 to 2002. Sediment deposition in the floodplain has decreased since the middle 1950's probably related to change from row crop agriculture to grazing. The floodplains are acting as significant sinks for the eroded material moving from the uplands and the floodplains are keeping eroded materials from reaching the stream channels or the bay. Plans need to be developed for these floodplains to insure that they remain a sink and do not become a source for eroded materials as improved management practices on the upland areas reduce sediment input to the floodplain.

Additional Keywords: erosion, sediment, ^{137}Cesium, watershed

Introduction
Major changes have occurred in the land use patterns in the Stemple Creek Watershed in northern California USA. Much of the riparian forests and marshes along the lower slopes and bottomlands near the stream channel were cleared and drained for agricultural purposes in the mid 1800's. Erosion in the uplands and along the streams increased and moved the eroding material to the floodplain, streams and bays (Harvey et al., 1990).

Stemple Creek is part of the coastal lands in the Bodega Bay-Tomales Bay area of northern California that has a long history of erosion and sedimentation problems. Geologically, the California coastal range is young and still uplifting at a rate of 0.07-0.08 cm yr^{-1}. The hills are prone to landslides, slumping, and erosion contributing to high naturally occurring erosion rates. Conversion of the moderately erodible soils to row crop agriculture and year-round grazing resulted in erosion with subsequent deposition in the floodplains, streams, and bays.

The AGNPS (AGricultural NonPoint Source) model was used to estimate erosion for four land use scenarios and estimated that 11% of the eroded material from the uplands reached Bodega Bay (Finney, 2002). Our study documents the recent sediment deposition patterns in the floodplains of Stemple Creek using the fallout ^{137}Cesium (^{137}Cs) dating technique.

Materials and Methods
Field Sites
Stemple Creek Watershed (Fig. 1) is located in Marin and Sonoma counties along the northern California coast, approximately 70 km north of San Francisco. Stemple Creek flows into Bodega Bay and the Pacific Ocean. The 134-km^2 watershed is characterized by rolling coastal hills with elevations ranging from sea level to 260 m and slopes ranging for 0 to 30%.

Annual precipitation ranges from 710 mm in the east to 915 mm along the Pacific coast with an average of 760 mm. 95% of the rainfall occurs between October and May. The native vegetation is a mix of perennial grasses with extensive patches of shrubs. This type of vegetation is described as coastal prairie-scrub or northern coastal shrub depending on the extent of the shrubs (NRCS, 2002). Agricultural crops and pastures have replaces the native prairie and riparian vegetation in many areas in the watershed. Heavy grazing led to the decline of the coastal prairie as Mediterranean annual grasses were introduced to replace the native prairie. While the coastal prairie was replaced with similar vegetation types like pasture and annual grasses, loss of riparian vegetation, which had stabilized stream banks and trapped sediments, contributed to eroding stream banks. These changes had an adverse effect on quality of the stream aquatic ecosystem and adjacent riparian corridor (NRCS, 2002).

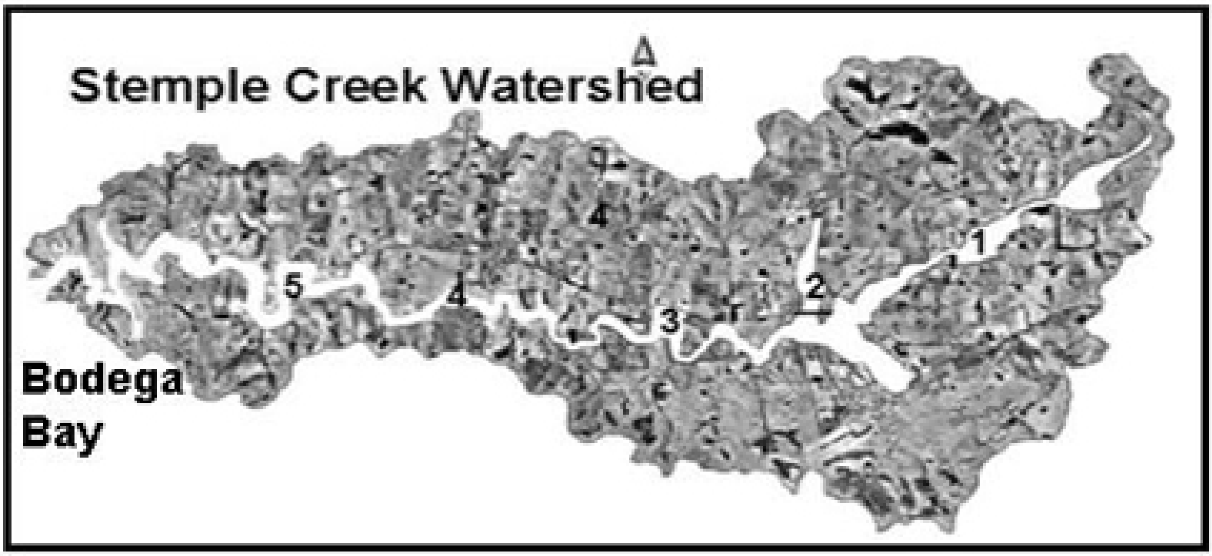

Figure 1. Stemple Creek Watershed showing the five sample cross section (See Table 2).
Floodplain is shown in white.

Soil surveys of Marin (Miller, 1972) and Sonoma (Kashiwagi, 1985) Counties, California show upland soils eroding and being deposited on the floodplain soils with Blucher (Fluvaquentic Haploxerolls) fine sandy loam and silt loam dominating the floodplains. The floodplain soils are enriched in organic matter on the surface and in buried layers and is stratified, an indication of frequent deposition.

The upland soils are residual soils that have eroded and are the source of sediment deposited in the floodplain. The dominant soils are the Steinbeck (Ultic Haplustalfs) and Sebastopol (Typic Haploxerults) soils series with slopes ranging from 2 to 15%. Both have an enrichment of clay in the subsoil with moderately slow permeability and have moderate runoff potential.

With rapidly increasing population in northern California beginning in the 1850s came agricultural activity. Early agricultural activities were ranching, dairy, and small grains. Early in the 20th century there was a large increase in cultivation with potatoes as the dominant crop. During the 1930s, chicken and egg production dominated. After World War II, much of the cultivated area was returned to pasture or allowed to return to native vegetation. A recent land use survey of Stemple Creek Watershed (NRCS, 2002) is given in Table 1.

Table 1. Land use of the Stemple Creek Watershed, California USA. (NRCS, 2002)

Land use	**Hectares**
Native vegetation	12335
Pasture	227
Dry farmed grain and hay	490
Cropland	146
Farmsteads/Urban	150
Total	13348

Sample collection and analysis
In November 2001 and March 2002, soil profiles were collected from five different floodplain areas (Figure 1) along Stemple Creek. Soil samples were collected in 5-cm depth increments. The soil samples were dried, sieved to pass a 2-mm screen, placed into Marinelli beakers, and sealed for ^{137}Cs analyses. Analyses for ^{137}Cs were made by gamma-ray analyses using a Canberra[1] Genie-2000 Spectroscopy System that receives input from three Canberra high purity coaxial germanium crystals (HpC >30 % efficiency). The system is calibrated and efficiency

[1] Trade names are included for the benefit of the reader and do not imply an endorsement of or a preference for the product listed by the U. S. Department of Agriculture.

determined using an Analytic[1] mixed radionuclide standard (10 nuclides) whose calibration can be traced to U.S. National Institute of Standards and Technology. Measurement precision for ^{137}Cs is ± 4 to 6%.

All ^{137}Cs in the environment is due to above ground nuclear weapon tests or release from nuclear reactors. The first measurable ^{137}Cs fallout from nuclear weapon tests began in 1954. Thus the deepest occurrence of ^{137}Cs in a depositional profile can be assigned a chronological date of 1954. A major peak of ^{137}Cs fallout deposition occurred in 1964 thus the section of a sediment profile which has the highest concentration of ^{137}Cs can be assigned a chronological date of 1964 (Ritchie and McHenry, 1990; Walling, 1999). These two chronological dates were used to calculate deposition rates for each depositional soil profiles collected.

The floodplain was divided into six similar sections based on similarities in topography, geomorphology, and cross section areas properties. Sections 1 to 5 were related to sites where soil profiles were sampled. Section 6 was at the lower end of the watershed as it enters Bodega Bay. The floodplain in this section was very different from the other sections and was not sampled. The area of each section was determined based on a Digital Elevation Map and used to estimate the total sediment deposited in the floodplain (Ritchie et al., In Press).

Results and Discussion

Distribution of ^{137}Cs in two of the floodplain sediment profiles is shown in Figure 1. A summary of the depth to the 1964 and 1954 deposition layers and the calculated sediment deposition rates is given in Table 2.

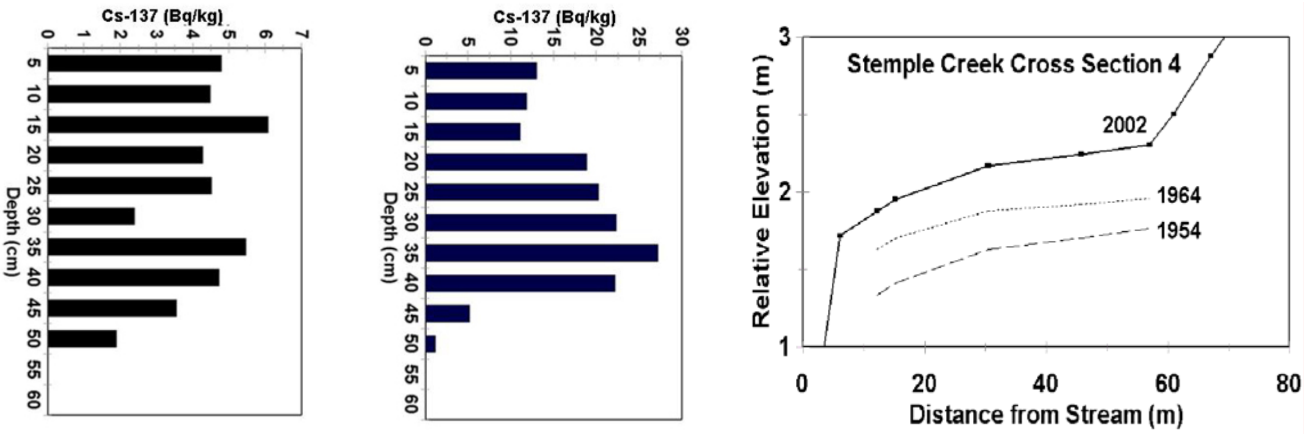

Figure 2. Distribution of ^{137}Cs by depth in profiles from Section 2 Site 1 (Left) and Section 5 Site 3(Center). An engineering surface survey (2002) of Cross Section 4 with estimated depths to the 1964 and 1954 deposition layers based on ^{137}Cs measurements is shown (Right).

Soil profiles were not collected deep enough to reach the 1964 layer at two sites or the 1954 layer at 5 sites, therefore sediment deposition rates for these profiles could not be estimated. Deposition rates ranged from 0.26 to 1.84 cm yr^{-1} for 1964 to 2002 period and an average of 0.85 ∀ 0.41 cm yr^{-1} for the 15 profiles that were deeper than the 1964 layer. Sediment deposition rates were higher for the 1954 to 1964 period with a range of 0.31 to 3.50 cm yr^{-1} and an average of 1.29 ∀ 1.04 cm yr^{-1} for 12 profiles that were deeper than the 1954 layer. Considering the fact that on 5 of the sediment profiles, depth to the 1954 layer could not be determined this average rate is probably underestimated. These data indicate that sediment deposition in the floodplain has decreased since the 1950s. This is consistent with the increase in pastures and a concurrent decrease of row crop agriculture that has occurred in the watershed (NRCS, 2002).

An example of the engineering survey of 2002 cross-section floodplain surface and the estimated cross section surface estimated for 1964 and 1954 based on the ^{137}Cs data is shown in figure 1 (right). Assuming that the average sediment deposition rates calculated from individual profiles along the cross section are representative of the deposition rate for the entire cross section then total sediment deposited in the floodplain of Stemple Creek can be calculated for the 1954 to 1964, 1964 to 2002, and 1954 to 2002 time periods (Table 3).

Table 2. Sediment deposition rates in the Stemple Creek floodplain calculated based on the depth to the 1964 and 1954 deposition layer determined from ^{137}Cs measurements.

Sample year, cross section number and site number	Depth to 1964 layer (cm)	Depth to 1954 layer (cm)	Deposition rate 1964-2002 (cm yr^{-1})	Deposition rate 1954-2002 (cm yr^{-1})	Deposition rate 1954-1964 (cm yr^{-1})
2002-1-1	70	75[a]	1.84	1.56[a]	0.50[a]
2002-1-2	50	55	1.32	1.15	0.50
2002-1-3	25	40	0.66	0.83	1.50
2001-1-1	40[a]	40[a]	1.05[a]	0.83[a]	0.83[a]
Average for section 1			1.22[a]	1.09[a]	0.83[a]
2002-2-1	35	50	0.92	1.04	1.50
2002-2-2	20	40	0.53	0.83	2.00
2001-2-1	15	25[a]	0.39	0.52[a]	1.00[a]
Average for section 2			0.61	0.80[a]	1.50[a]
2002-3-1	25	40	0.66	0.83	1.50
2002-3-2	20	45	0.53	0.94	2.50
2002-3-3	25	35	0.66	0.73	1.00
2001-3-1	10	40	0.26	0.83	3.00
Average for section 3			0.53	0.83	2.00
2002-4-1	25	60[a]	0.66	1.25[a]	3.50[a]
2002-4-2	35	55	0.92	1.15	2.00
2001-4-1	60[a]	60[a]	1.58[a]	1.25[a]	1.25[a]
Average for section 4			1.05[a]	1.22[a]	2.25[a]
2002-5-1	15	15	0.39	0.31	0.31
2002-5-2	35	35	0.92	0.73	0.73
2002-5-3	35	50	0.92	1.04	1.50
Average for section 5			0.75	0.69	0.85

[a] Values are under estimated because the soil profile did not extend below where ^{137}Cs concentrations reached zero.

Table 3. Total estimated sediment deposition in Stemple Creek Watershed floodplain, 1954 to 2002.

Section	Hectares	Deposition rate cm yr^{-1}	Bulk density g cm^{-3}	Metric Tons $*10^3$ yr^{-1} $Section^{-1}$	Metric Tons $* 10^3$ $Section^{-1}$	Metric Tons yr^{-1} ha^{-1}
Calculated Floodplain Deposition from 1964 to 2002						
1	539.1	1.22	1.46	95.8	3640.4	177.7
2	97.3	0.61	1.31	7.8	297.3	80.2
3	177.8	0.53	0.93	8.7	330.5	48.9
4	52.6	1.05	0.99	5.5	208.4	104.6
5	124.7	0.75	1.11	10.3	392.4	82.6
Total	991.5			128.1	4868.8	129.2
Calculated Floodplain Deposition from 1954 to 2002						
1	539.1	1.09	1.46	86.1	4133.1	159.7
2	97.3	0.80	1.31	10.2	488.8	104.7
3	177.8	0.83	0.93	13.8	661.2	77.5
4	52.6	1.22	0.99	6.3	303.7	120.3
5	124.7	0.69	1.11	9.6	461.1	77.0
Total	991.5			126.0	6047.9	127.1
Calculated Floodplain Deposition from 1954 to 1964						
1	539.1	0.83	1.46	65.3	653.3	121.2
2	97.3	1.50	1.31	19.1	191.2	196.5
3	177.8	2.00	0.93	33.1	330.7	186.0
4	52.6	2.25	0.99	11.7	117.2	222.8
5	124.7	0.85	1.11	11.8	117.7	94.4
Total	991.5			141.0	1410.0	142.2

Sediment deposition rates were higher on Sections 1 and 4 (Table 3) than the other Sections for the 1964 to 2002 period. Section 1 is in the large floodplain section in the upper end of the watershed where extensive row crop agriculture had occurred and where grazing now dominates. The soil profile description shows a deep loam soil with slopes of less than 2%. Section 4 is also in a very broad floodplain area and has a deep loamy sandy with 2-5% slope. The other 3 Sections had deposition rates that were 25 to 50% lower. These 3 sections are also relatively narrow.

Sections 3 and 4 had sediment deposition rates of 2 cm yr^{-1} or greater for the 1954 to 1964 time period. Sediment deposition rates were higher for the 1954 to 1964 time period for all cross section except Section 1. Since two of the four profiles collected for Cross Section 1 did not reach the 1954 layer it is assumed that the deposition rate for Section 1 is probably underestimated for the 1954 to 1964 time period. These measurements are reflective of the changing land use pattern from row crop agriculture to pasture.

Deposition rate in the total floodplain for the 1964 to 2002 time period was 129 mt ha^{-1} yr^{-1}. Deposition rates were higher for the 1954 to 1964 time period with a total of 142 mt ha^{-1} yr^{-1} for the floodplain (Table 3). The pattern of deposition changed over time. From 1954 to 1964, the rate of deposition was highest in section 4 and from 1964 to 2002 highest in section 1. Average deposition per unit area was 10% higher for the 1954-1964 period than the 1964 to 2002 period.

Estimated total deposition in the floodplain area was $128x10^3$ mt yr^{-1} for the period between 1964 and 2002 and $141x10^3$ mt yr^{-1} for 1954 to 1964 (Table 3). Finney (2002) using AGNPS model estimated total erosion of $227x10^3$ mt yr^{-1} with a sediment delivery to the Bodega Bay estimated to be $26x10^3$ mt yr^{-1}. Comparing our measured floodplain deposition with the AGNPS estimated total erosion from the watershed, 56 or 62 % (1964-2002 or 1954-1964 time periods) of the AGNPS estimated total erosion has been deposited in the floodplain. With 11% of AGNPS estimated erosion being delivered to end of the watershed, this leaves 33 or 27% of the AGNPS estimated erosion somewhere else in the watershed. AGNPS accounts for eroded material delivered to the edge of landscape cell but does not account for eroded material that may be redeposited within a landscape cell. Significant redeposition of eroded material has been shown to occur within the same field and never reach the edge of the field (He and Walling, 2003; Ritchie and McCarty, 2003; Walling et al., 2003). This redeposition within the field may account for much of the difference between our measured floodplain deposition and the AGNPS estimated erosion.

Other studies in northern California coastal watershed have estimated sediment delivery ratios between 6 and 50% (Lewis, 2002). An earlier study by NRCS (SCS, 1992) on the Stemple Creek watershed estimated sediment delivery to Bodega Bay of $46x10^3$ mt yr^{-1} almost double that estimated from the AGNPS model estimates. If we assume a higher sediment delivery ratio than was calculated by the AGNPS model then we would account for more, but not all, of the eroded material from the watershed. However, we have no physical measurements from our study other than the sediment deposited in the floodplain to use as a basis for determining a sediment delivery ratio for the Stemple Creek Watershed. We can only note that there is some uncertainty as to the sediment delivery ratio for the watershed along the northern California coast.

Combining our measurements of floodplain deposition and the AGNPS (Finney, 2002) estimated delivery to the end of the watershed give total sediment deposition $167x10^3$ mt yr^{-1} for 1954 to 1964 and of $154x10^3$ mt yr^{-1} for the period between 1964 and 2002. An erosion rate of 12.5 mt ha^{-1} yr^{-1} for the 1954-1964 period and 11.5 mt ha^{-1} yr^{-1} on the watershed would be needed to produce this amount of soil for deposition for the 1964-2002 time period. The AGNPS estimated erosion rates were 17.0 mt ha^{-1} yr^{-1} for the watershed (Finney, 2002). These erosion rates appear to be reasonable for a watershed that has been in pasture for the last 40 years and are consistent with the T values between 2.2 and 11.2 mt ha^{-1} yr^{-1} for the soil of the watershed (NRCS, 2002).

Conclusions

Stemple Creek's floodplains are a significant sink for the eroding soils from the uplands. Deposition rates of 1 to 2 cm yr^{-1} were measured for the period between 1954 and 2002. Such deposition rates are not unusual for floodplains (Ritchie et al., 1975; Owens et al., 1999; Walling, 1999). Floodplain deposition accounts for over 50% of the soils estimated to be eroding from the watershed using the AGNPS model. Given the significance of the floodplain for trapping eroded material before it reaches stream channels and the Bay, plans are needed that will insure that these floodplains remain a sink and do not become a source for eroded materials as improved management practices on the upland areas reduce sediment input to the floodplain

Acknowledgements
The authors would like to thanks the staff of the Petaluma NRCS Field Office for their assistance in interfacing with the Agricultural Producers and the Farmers of Stemple Creek Watershed who allowed us access to their farms. Special thanks goes to Charlette Sanders NRCS District Conservationist at the Petaluma Field Office for her cooperation and for reviewing several early versions of this manuscript. Thanks also goes to Paul Pedone, NRCS State Geologist for Oregon who provided help, guidance, and insights on our first trip to the Stemple Creek Watershed and commented on earlier versions of the manuscript.

References
Finney, V. (2002). *AGNPS modeling of Stemple Creek Watershed, CA*. NRCS Technical Report, California NRCS Watershed Planning Staff, 430 G St., Davis, CA.

Harvey, H.T. (1990). *Evolution of wetlands in the Estero Americano, long-term detailed wastewater reclamation studies. Santa Rosa Subregional Water Reclamation System*. Draft NRCS Technical Memorandum No.W9, Santa Rosa, CA.

He, Q. and Walling, D.E. (2003). Testing distributed soil erosion and sediment delivery models using ^{137}Cs measurements. *Hydrological Processes* 17, 901-916.

Kashiwagi, J.H. (1985). *Soil Survey of Marin County, California*. United States Department of Agriculture, Soil Conservation Service, Davis, CA. March 1985.

Lewis, J. (2002). Quantifying recent erosion and sediment delivery using probability: A case study. *Earth Surface Processes and Landforms* 27, 559-572.

Miller, V.C. (1972). Soil Survey of Sonoma County, California. United States Department of Agriculture, Forest Service and Soil Conservation Service, Davis, CA. May 1972.

NRCS (Natural Resources Conservation Service). (2002). *Stemple Creek Watershed Project, Marin and Sonoma counties, California: Draft Watershed Project Plan and Environmental Assessment*. USDA Natural Resources Conservation Service, Davis, CA, 54pp.

Owens, P.N., Walling, D.E. and Leeks, G.J.L. 1999. Use of floodplain sediment cores to investigate recent historical changes in overbank sedimentation rates and sediment sources in the catchment of the River Ouse, Yorkshire, UK. *Catena* 36, 21-47.

Ritchie, J.C., Hawks, P.H. and McHenry, J.R. (1975). Deposition rates in valleys determined using fallout Cs-137. *Geology Society of America Bulletin* 86, 1128-1130.

Ritchie, J.C. and McCarty, G.W. (2003). ^{137}Cesium and soil carbon in a small agricultural watershed. *Soil and Tillage Research* 69, 45-51.

Ritchie, J.C. and McHenry, J.R. (1990). Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A review. *Journal of Environmental Quality* 19, 215-233.

Ritchie, J.C., Finney, V.L., Oster, K.J., and Ritchie, C.A. (In Press) Sediment deposition in the flood plain of Stemple creek watershed, northern California. *Geomorphology*

SCS (Soil Conservation Service). (1992). *Stemple Creek Watershed erosion and sediment study, Marin and Sonoma counties. SCS Technical Report*, USDA Soil Conservation Service, Davis, CA.

Walling, D.E. (1999). Using fallout radionuclides in investigations of contemporary overbank sedimentation on the floodplains of British rivers. In: Marriott, S.B. and Alexander, J. (eds.), *Floodplains: Interdisciplinary Approaches,* Special Publications vol. 163, pp. 41-59. Geological Society, London,.

Walling, D.E., He, Q. and Whelan, P.A. (2003). Using ^{137}Cs measurements to validate the application of the AGNPS and ANSWERS erosion and sediment yield models in two small Devon catchments. *Soil and Tillage Research* 69, 27-43.

Walling, D.E., Owens, P.M. and Leeks, G.J.L. (1999). Rates of contemporary overbank sedimentation and sediment storage on the floodplains of the main channel systems of the Yorkshire Ouse and River Tweed, UK. *Hydrological Processes* 13, 993-1009.