ARTICLE IN PRESS

Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Geomorphology xx (2004) xxx–xxx

GEOMORPHOLOGY

www.elsevier.com/locate/geomorph

Sediment deposition in the flood plain of Stemple Creek Watershed, northern California

Jerry C. Ritchie[a,*], Vernon L. Finney[b], Kenneth J. Oster[c], Carole A. Ritchie[d]

[a] *USDA ARS Hydrology and Remote Sensing Laboratory, Beltsville, MD 20705, USA*
[b] *USDA NRCS California State Office, Davis, CA 95616, USA*
[c] *USDA NRCS Templeton Service Center, Templeton, CA 93465, USA*
[d] *Botanical Consultant, Laurel, MD 20708, USA*

Received 16 July 2003; received in revised form 27 January 2004; accepted 30 January 2004

Abstract

Over the past 150 years, major land use changes have occurred in the Stemple Creek Watershed in northern California that have caused erosion to move soils from the upland to the flood plain, stream channels, and the bay. The purpose of this study is to document the recent (1954 to present) sediment deposition patterns in the flood plain area adjacent to Stemple Creek using the ^{137}Cesium technique. Sediment deposition ranged from 0.26 to 1.84 cm year^{-1} for the period from 1964 to 2002 with an average of 0.85 ± 0.41 cm year^{-1}. Sediment deposition rates were higher for the 1954 to 1964 period with a range of 0.31–3.50 cm year^{-1} and an average of 1.29 ± 1.04 cm year^{-1}. These data indicate that sediment deposition in the flood plain has decreased since the middle 1950s, probably related to reduction in row crop agriculture and an increase in pasturelands. This study shows that the flood plains in the Stemple Creek Watershed are a significant sink for the soils being eroded from the upland area. Given the significance of the flood plain for trapping eroded materials before they reach the stream channels or the bay, efforts need to be made to manage these flood plain areas to insure that they do not change and become a source rather than a sink for eroded materials as improved management practices on the upland areas reduce sediment input to the flood plain.

Keywords: Flood plain; Deposition; Erosion; ^{137}Cesium; California

---

1. Introduction

Over the past 150 years, major changes have occurred in the land use patterns in the Stemple Creek Watershed in northern California. Riparian forests and marshes are believed to have been more widespread in the areas adjacent to the stream channel of the Stemple Creek Watershed. Much of these lower slopes and bottomlands were cleared and drained for agriculture in the 1860s. Erosion accelerated under these conditions and stream channels and bays filled with sediment, further reducing the area occupied by riparian forests and marshes (Harvey, 1990).

Stemple Creek is part of the coastal lands in the Bodega Bay–Tomales Bay area that has a long history of erosion and sedimentation problems. Geologically, the California coastal range is young and still uplifting. A coastal uplift rate of 0.07–0.08 cm

---

* Corresponding author. Tel.: +1-301-504-7940; fax: 1-301-504-8930.

E-mail address: jritchie@hydrolab.arsusda.gov (J.C. Ritchie).

0169-555X/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2004.01.009

year^{-1} has been calculated for the Point Reyes Peninsula, CA (K. Grove, Department of Geoscience, San Francisco University, personal communication, 2001). The hills are therefore prone to landslides, slumping, and erosion contributing to high naturally occurring erosion rates. In addition, historically the combination of row crop agriculture, cultivation, and year-round grazing on moderately erodible Steinbeck (Mollic Haploxeralfs), Sebastopol (Typic Haploxerults), and Tomales (Ultic Paleustalfs) soils has resulted in erosion on the watershed with subsequent sediment deposition in the flood plains, stream channels, and bays causing loss of open water. In the late 19th and early 20th century, Estero Americano, north of Estero de San Antonio, was a navigable waterway used to ship produce from the area. Today, the Estero is too shallow for large boats.

During the middle to late 1880s, the land was used for growing a wide variety of crops. In the early to mid-1900s, potatoes were grown extensively. Farming over the last 50 years has evolved to primarily dairy operations and grazing of sheep, beef cattle, and replacement dairy heifers. Grazing pressure has been reduced from historic high levels; but where animals are concentrated for extended periods or where soils are wet, livestock continue to cause erosion problems. This is more prominent in the upper flood plain reaches of the watershed. Restoration and conservation efforts are underway by landowners on the watershed. The Marin and Southern Sonoma County Resource Conservation Districts and landowners have completed 13 km of riparian restoration projects in the last 10 years along the waterways. The U.S. Department of Agriculture (USDA), National Resource Conservation Service (NRCS) approved 24 Environmental Quality Incentives Program (EQIP) contracts to improve conservation of the land within the watershed between 1997 and 2002.

This history of land use impacting erosion is superimposed on the geological controls of erosion and sedimentation. The Stemple Creek Watershed is a truncated watershed. Travis (1952) reported that the watershed of Stemple Creek formerly extended to Santa Rosa Mountain. As a larger stream, Stemple Creek was able to keep pace with tectonic uplift and incised a deep sinuous canyon in the coastal hills before discharging to the Pacific Ocean. Later tectonic uplift occurring inland truncated the drainage (Prunuske-Chatham, 1994). The present low gradient stream system (0.000415 m m^{-1}) is conducive to deposition, confirmed by sediment in-filled stream channels in the upper watershed. As Stemple Creek flows coastward, the fjord-like qualities of steep and twisting uplands become the dominating character of the landscape.

Finney (2002) used the AGricultural NonPoint Source (AGNPS) model to estimate soil loss for four land use scenarios and estimated that 11% of the eroded material from the uplands reached the bay. The purpose of this study is to document the recent (1954 to present) sediment deposition patterns in the flood plain area adjacent to Stemple Creek using the radioactive fallout ^{137}Cesium (^{137}Cs) dating technique. Using ^{137}Cs, sediment layers deposited in 1954 and 1964 can be determined and sedimentation rates and patterns can be determined (Ritchie and McHenry, 1990; Walling and He, 1993; Walling et al., 1999).

2. Study area

2.1. Setting and landscape

Stemple Creek Watershed is located in Marin and Sonoma Counties on the northern California coast and covers 134 km^2. Stemple Creek flows from east to west into the Estero de San Antonio and ultimately flows into Bodega Bay and the Pacific Ocean. Stemple Creek Watershed is characterized by rolling coastal hills with slopes averaging about 30%. Elevations range from sea level at the mouth of the Estero de San Antonio to 100 m at the eastern end of the watershed, 200 m along the northern boundary, and 260 m along the southern boundary.

Two geologic formations, the Franciscan and Wilson Grove, underlie the watershed. The Franciscan formation of Mesozoic age is the older and consists of a mixture of rock masses in a sheared, shaley matrix and is fractured and faulted. These rocks are found mostly at lower elevations and in the western end of the watershed. The Wilson Grove formation is of Pliocene age and is mostly marine sediments consisting of sandstones, conglomerates, limestone concretions, and tuffs. These rocks make up the largest part of the watershed. They are found at higher elevations and are generally in the eastern end of the watershed (NRCS, 2002).

Upland hillsides bordering Stemple Creek to a point roughly 2 km from the mouth of the Estero de San Antonio provide a combination of varied and relatively undisturbed landscape. The stream in this area has fjord-like qualities of steep and twisting uplands as the dominating characteristic. The interspersion of coastal prairie, coastal scrub, riparian ravines and seeps, coastal strand, and grassland in the area creates high habitat value for wildlife. In addition, restricted public access has left these areas relatively undisturbed, further enhancing their attractiveness to wildlife. Numerous freshwater seeps occur along the hillsides of Estero de San Antonio. Along with the numerous riparian ravines, these moist areas increase vegetational diversity and biomass and provide valuable wildlife habitat in the dry upland areas. The watershed includes 1860 ha of farmland located in the valley bottoms near the streams (NRCS, 2002).

Mean annual precipitation ranges from 710 mm in the east to 915 mm in the west, with an average of 760 mm. Ninety-five percent of the rainfall occurs between October and May.

2.2. Vegetation

The Stemple Creek Watershed is a highly diversified watershed, containing 21 different habitat types. Most of the land draining directly into Stemple Creek is gently sloping grasslands (Prunuske-Chatham, 1994). The most significant wildlife habitats are the riparian areas. They are distinctly different from the surrounding lands because of unique soil and vegetation characteristics that are strongly influenced by water in the soil (CAFG, 1977).

The natural vegetation in the area is a mix of native perennial grasslands with extensive patches of shrubs. This type of vegetation is described as coastal prairie-scrub or northern coastal shrub depending on the relative extent of the shrubs. Its composition is complex and varies depending on slope, solar exposure, nearness to the coast, and fire history. Generally, the dominant perennial grasses in this type are California oatgrass [*Danthonia californica* Bol.], Idaho fescue [*Festuca idahoensis* Elmer subsp. *idahoensis*], and red fescue [*Festuca rubra* L. subsp. *rubra*]. The major shrub species are coyote brush [*Baccharis pilularis* DC.] with significant amounts of poison oak [*Toxicoodendron diversilobum* (Torr. & A. Gray) Greene], lupine [*Lupinus* spp.], and blackberry [*Rubus* spp.]. Native woodlands are confined to the upper watershed, especially the north-facing slopes, and along streams as riparian zones. These vegetation types formed a mosaic, which was very stable over time until agriculture was introduced. Several native plant species that are uncommon or that reach the southern most limit of their distribution in this area are locally common in the coastal prairie. These include the native perennial grasses: California fescue [*Festuca californica* Vasey], Pacific reed grass [*Calamagrostis nutkaensis* (J. Presl & C. Presl) Steud.], tufted hairgrass [*Deschampsia cespitosa* (L.) P. Beauv.], Oregon gentian [*Gentiana affinis* Griseb. var. *ovata* A. Gray] and pickleweed [*Salicornia europaea* L.]. Swamp thistle [*Cirsium douglasii* DC. var. *breweri* (A. Gray) Keil & C. Turner], known from only one other spot in Marin County, occurs in the seep areas along the lower parts of the watershed (CAFG, 1977).

Four major factors led to drastic changes in this native coastal prairie. These were (i) cultivation, (ii) an increase in grazing, (iii) the introduction of highly competitive non-native vegetation after overgrazing, and (iv) the elimination of frequent light fires. Heavy grazing pressure led to the decline of the coastal prairie as introduced Mediterranean annual grasses replaced the native plants. Native prairie and riparian vegetation were virtually eliminated from the watershed in areas that were converted to crops and pasture. While the coastal prairie was replaced with similar vegetation types like pasture and annual grasses, loss of riparian vegetation contributed to eroding stream banks by decreasing streamside vegetation that formerly trapped sediment and stabilized the stream bank. This has had adverse impacts on the quality of the aquatic ecosystem and adjacent riparian corridor. Most wildlife in and along the steam corridor depends on or favors the varied plant species composition during part of their life cycle (NRCS, 2002).

Perhaps the single most detrimental impact on the watershed's streams and sediment yields to the Estero de San Antonio was the excavation of channels in the upper watershed bottomlands, draining meadows to

Table 1
Soils of the lower Stemple Creek Watershed flood plain[a]

County	Landform	Map symbol	Soil name	% Slope	Soil profile		Soil hydrologic group	Taxonomic classification	Land use	Deposition	Flooding		
					Depth (cm)	Texture					Frequency	Duration	Months
Sonoma	Basin along stream bottoms, alluvial fans	BcA	Blucher	0 to 2	0–51 51–86	Fine sandy loam Fine sandy loam	C	Fluvaquentic Haploxerolls	Pasture, row crops	Overwash	Occasional	Very brief	Dec.–Apr.
Sonoma	Basin along stream bottoms, alluvial fans	BhB	Blucher	2 to 5	0–23 23–51 51–86	Loam Silt loam Fine sandy loam	C	Fluvaquentic Haploxerolls	Hay, field corn		Occasional	Very brief	Dec.–Apr.
Sonoma	Basin along stream bottoms, alluvial fans	BlB	Blucher	2 to 5	0–51 51–86 86–152	Clay loam Fine sandy loam Clay loam, silty clay loam	C	Fluvaquentic Haploxerolls	Annual pasture, short season crops		Occasional	Very brief	Dec.–Apr.
Marin	Basin, alluvial fans	105	Blucher	2 to 5	0–18 18–58 58–152	Silt loam Loam, silt loam, fine sandy loam Clay loam, silty clay loam	C	Fluvaquentic Haploxerolls	Grazing, hay, pasture		Occasional	Very brief	Dec.–Apr.
Marin	Basin, alluvial fans	105	Cole	2 to 5	0–13 13–36 36–152	Clay loam Silty clay loam, clay loam, clay Silty clay loam, clay loam, silty clay	C	Pachic Argixerolls	Grazing, hay, pasture		Occasional	Brief	Nov.–Mar.

[a] Soils are listed in order of increasing slope and higher landscape position. Land use is from 1956 through 1964 for Sonoma County and from 1973 through 1978 for Marin County (Miller, 1972; Kashiwagi, 1985).

Table 2
Land use of the Stemple Creek Watershed, Sonoma and Marin County, CA (NRCS, 2002)

Land use	Hectares
Native vegetation	12,335
Native pasture	154
Mixed pasture	73
Dry farmed grain and hay	490
Cropland	146
Farmsteads/Urban	150
Total	13,348

allow cropping and grazing. Because of the flat gradient, these channels are now filling with sediment. AGNPS modeling results (Finney, 2002) depict the depositional nature of these stream reaches.

2.3. Soils

Soil surveys of Marin (Miller, 1972) and Sonoma (Kashiwagi, 1985) Counties, CA, give the context of upland soils eroding and being deposited on the flood-plain soils, in the Estero de San Antonio, or in the bay. The flood-plain soils (Table 1) are alluvial soils along stream bottoms and on alluvial fans. Slope ranges from 0% to 5%. Blucher (Fluvaquentic Haploxerolls) fine sandy loam and silt loam dominates the Stemple Creek flood plain. This soil is stratified, indicating it has received frequent deposition during its formation. This soil has enriched organic matter on the surface as well as in buried surface layers. The soil is saturated for a significant time during the growing season at places in the root zone. The primary map unit (BcA) is an overwash phase indicating recent deposition. Flood frequency is 5 to 50 times in 100 years. These occasional floods would deposit sediment at the same frequency. Another flood-plain soil is Cole (Pachic Argixerolls), which is closely associated with the Blucher (Table 1).

The upland soils are mostly residual soils on terraces and uplands that have eroded and are the source of sediment deposited in the flood plain. These soils include the Steinbeck (Ultic Haplustalfs) and Sebastopol (Typic Haploxerults) soils series. Slopes range from 2% to 15%. Both have an enrichment of clay in the subsoil with moderately slow permeability. Both are in soil hydrologic group B, which has moderate runoff potential. Other upland soils include the Los Osos (Typic Argixerolls), Sobega (Udic Ustochrepts), Tomales (Ultic Paleustalfs), and Yorkville (Typic Argixerolls) soil series. Slopes range from 2% to 50%. Except for the Sobega series, all these soils have an enrichment of clay in their subsoils and have moderate to very

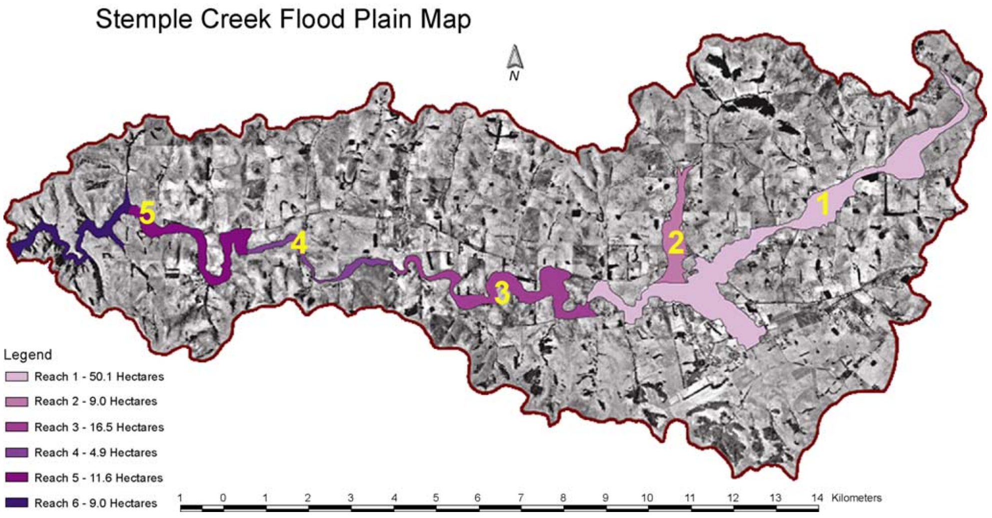

Fig. 1. Map of Stemple Creek Watershed showing location of sampling cross section (numbers) and the reaches (colors) of the flood plain that was associated with each sample cross section.

slow permeabilities. In addition, all soils are moderately deep to weathered sedimentary rock. Most of the watershed is in soil hydrologic groups B, C, and D, which have moderately high to high runoff potential.

2.4. Agricultural history

Agricultural activity in and around the watershed began accelerating around 1850 with increasing population in northern California because of the gold rush. Major agricultural activities were ranching, dairy, and small grains. Throughout the latter half of the 19th century, ranchers raised cattle and sheep and grew hay and grains for livestock feed. Dairies, small farms, and orchards produced milk, potatoes, fruit, and vegetables for commercial use (NRCS, 2002).

The first half of the 20th century saw a large increase in the area cultivated to produce crops with potatoes the dominant crop for the first half of the century. During the 1930s, the area became known for chicken and egg production. After World War II, much of the cultivated area was returned to pasture for dairy, beef, and sheep. Table 2 shows a recent land use mapping of Stemple Creek Watershed (NRCS, 2002).

3. Methods and materials

In November 2001, soil profiles were collected from four different flood plain areas (sites 1–4) along Stemple Creek (Fig. 1). Soil profile samples were collected by digging pits and collecting soil samples in 5-cm increments from the side of the pits. One sample profile was collected in each flood plain area. A description of the soil profiles was also made (Tables 3–6). An engineering survey of the relative surface elevation of the flood-plain cross section from streambank to the edge of the flood plain was made using standard surveying techniques.

Table 3
Description of a soil profile at Stemple Creek flood-plain cross section 1

Site number	Stemple Creek # 1
Location	Carl Graham Property, 2865 Pepper Road, Sonoma County, CA
Date of description	November 4, 2001
Landform	Flood plain
Soil map unit	BcA-Blucher fine sandy loam, overwash, 0 to 2% slope
Classification	Fluvaquentic Haploxerolls
Samples	5-cm increments from 0 to 40 cm

Horizon	Depth (cm)	Color (moist)		Texture	Structure	Consistence		Horizon boundary	Unified class
		%	Munsell			Moist	Wet		
Ap	0–13	100	10YR 4/2	Sandy loam	Moderate fine granular	Friable	Non-sticky, non-plastic	Clear, smooth	SM
Cg	13–30	70 30	10YR 4/2 10YR 4/4	Sandy loam	Strong fine and medium subangular blocky	Friable	Non-sticky, non-plastic	Abrupt, smooth	SM
Ab	30–36	100	10YR 3/2	Loam	Strong fine subangular blocky	Friable	Sticky, plastic	Abrupt, smooth	ML
Cg’	36–90	90 10	2.5YR 3/2 2.5YR 4/4	Loam	Moderate fine and medium subangular blocky	Firm	Sticky, plastic	NA	ML

Table 4
Description of a soil profile at Stemple Creek flood-plain cross section 2

Site number	Stemple Creek # 2
Location	Paul Martin Property, 8090 Two Rocks Road, Sonoma County, CA
Date of description	November 4, 2001
Landform	Flood plain
Soil map unit	BcA-Blucher fine sandy loam, overwash, 0 to 2% slope
Classification	Fluvaquentic Haploxerolls
Samples	5-cm increments from 0 to 30 cm

Horizon	Depth (cm)	Color (moist)		Texture	Structure	Consistence		Horizon boundary	Unified class
		%	Munsell			Moist	Wet		
Ap	0–6	100	10YR 3/2	Fine sandy loam	Moderate medium platy	Firm	Slightly sticky, slightly plastic		SM
C	6–16	100	10YR 4/2	Fine sandy loam	Moderate medium subangular blocky	Friable	Slightly sticky, slightly plastic		SM
Cg1	16–52	90 10	10YR 4/2 10YR 5/2	Fine sandy loam	Moderate course subangular blocky	Firm	Slightly sticky, slightly plastic		ML
Cg2	52–90	90 10	2.5YR 5/2 2.5YR 3/2	Stratified fine sandy loam and silty clay loam	Weak medium platy	Friable	Non-sticky, slightly plastic		Stratified SP-SM CL
Ab	90+	100	2.5YR 3/1	Silty clay loam	Strong medium subangular blocky	Friable	Sticky, plastic		CL

In March 2002, soil profiles (Fig. 1) were collected in the same four flood plain areas (site 1–4) and in a flood plain area further down stream (site 5). These soil samples were collected by driving a 10-cm plastic pipe into the soil. The pipe was extracted and cut into 5-cm increments. Either two or three soil profiles were collected on each of the five flood-plain cross sections. Again, engineering surveys of the relative surface elevation across the flood-plain cross sections were made.

The soil samples were dried, sieved to pass through 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 (with Windows-based software packages) that receives input into three 8192-channel analyzers from Canberra high purity coaxial germanium crystals (HpC>30% efficiency). The system is calibrated and efficiency determined using an Analytic[1] mixed radionuclide standard (10 nuclides) whose calibration can be traced to U.S. National Institute of Standards and Technology. ^{137}Cesium is detected at 0.662 meV, and counting time for each sample provides a measurement precision of ± 4% to 6%. Estimates of radionuclide concentrations of the samples are made using Canberra Genie-2000 software.

All ^{137}Cs in the environment is due to aboveground nuclear weapon tests or release from nuclear reactors. The first measurable fallout from nuclear weapon tests occurred in 1954. Thus, the deepest occurrence of ^{137}Cs in a sediment profile can be assigned a chrono-

---

[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.

Table 5
Description of a soil profile at Stemple Creek flood-plain cross section 3

Site number	Stemple Creek # 3
Location	Francis Righetti Property, 155 Twin Bridge Road, Marin County, CA
Date of description	November 4, 2001
Landform	Flood plain
Soil map unit	105-Blucher-Cole complex, 2 to 5% slope
Classification	Fluvaquentic Haploxerolls—Pachic Argixerolls
Samples	5-cm increments from 0 to 40 cm

Horizon	Depth (cm)	Color (moist)		Texture	Structure	Consistence		Horizon boundary	Unified class
		%	Munsell			Moist	Wet		
Ap	0–9	100	10YR 3/2	Loam	Moderate coarse granular	Firm	Slightly sticky, slightly plastic	Clear, smooth	ML
A	9–28	100	10YR 3/2	Clay loam	Moderate medium subangular blocky	Firm	Sticky plastic	Clear, smooth	ML-CL
Cg	28–35		10YR 4/2 10YR 3/1 10YR 4/3	Fine sandy loam	Moderate fine and medium	Friable	Slightly sticky, slightly plastic	Abrupt, smooth	SM
Ab	35–70	100	10YR 2/1	Light clay loam	Moderate coarse prismatic	Friable	Sticky plastic	NA	ML-CL

Table 6
Description of a soil profile at Stemple Creek flood-plain cross section 4

Site number	Stemple Creek # 4
Location	Al Poncia Property, 28900 Highway 1, Marin County, CA
Date of description	November 4, 2001
Landform	Flood plain
Soil map unit	105-Blucher-Cole complex, 2 to 5% slope
Classification	Fluvaquentic Haploxerolls—Pachic Argixerolls
Samples	5-cm increments from 0 to 60 cm

Horizon	Depth (cm)	Color (moist)		Texture	Structure	Consistence		Horizon boundary	Unified class
		%	Munsell			Moist	Wet		
Ap	0–12	100	2.5Y 4/2	Fine sandy loam	Moderate fine and medium subangular blocky	Friable	Non-sticky, non-plastic	Clear, smooth	SM
C	12–34	85 15	10YR 4/3 10YR 4/4	Fine sandy loam	Moderate medium and coarse subangular blocky	Friable	Non-sticky, non-plastic	Clear, smooth	SM
Cg	34–110	80 20	2.5Y 4/2 2.5Y 4/4	Fine sandy loam	Massive	Friable	Non-sticky, non-plastic	NA	SM

logical date of 1954. A major peak of ^{137}Cs fallout deposition occurred in 1964. The section of a sediment profile that has the highest concentration of ^{137}Cs can be assigned a chronological date of 1964 (Ritchie et al., 1973). Thus, two chronological dates can be determined in most sediment profiles. We used this technique to determine these two chronological dates for the sediment profiles that were collected from Stemple Creek flood plain and calculated deposition rates based on these two dates (Ritchie et al., 1973; Ritchie and McHenry, 1990; Owens et al., 1999; Walling et al., 1999).

A Digital Elevation Map (DEM) was used to delineate the flood plain of the Stemple Creek Watershed based on elevation. The flood plain area was divided into six reaches (areas) (Fig. 1) based on geomorphic similarity and similarities to the cross-section areas where soil profiles were collected. Reaches 1 to 5 were related to sampled cross section sites 1 to 5 on the flood plain. Reach 6 was at the lower end of the watershed as it enters the Bodega Bay and was not sampled. The area of each reach was calculated and used to estimate the total sediment deposited in each reach.

4. Results and discussion

Examples of the distribution of ^{137}Cs in the flood-plain sediment profiles are shown in Figs. 2 and 3. A summary of the depth to the 1964 and 1954 deposition layers and the calculated sediment deposition rates is given in Table 7. In two of the sediment profiles, samples were not collected deep enough to reach the 1964 layer. In five of the profiles, samples were not collected deep enough to reach the 1954 layer. Therefore, sediment deposition rates for those profiles could not be determined.

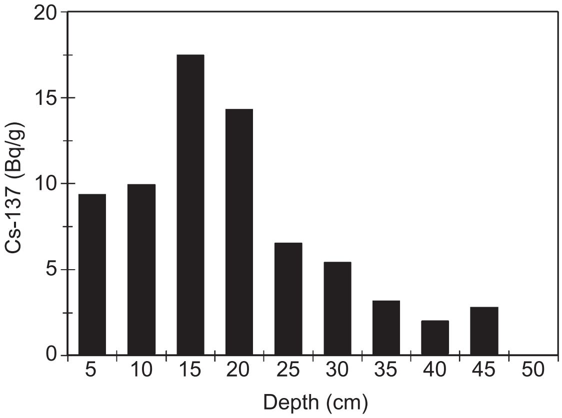

Fig. 2. Distribution of ^{137}Cs by depth in a flood-plain soil collected on Stemple Creek cross section 3 site 2. Locations of the 1964 and 1954 deposition layers are shown.

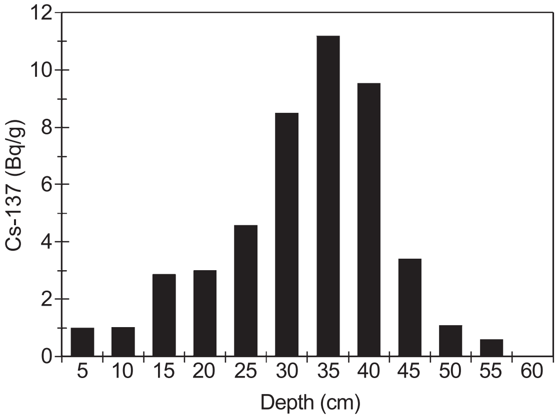

Fig. 3. Distribution of ^{137}Cs by depth in a flood-plain soil collected on Stemple Creek cross section 4 site 2. Locations of the 1964 and 1954 deposition layers are shown.

Sediment deposition ranged from 0.26 to 1.84 cm year^{-1} for the period from 1964 to 2002 with an average of 0.85 ± 0.41 cm year^{-1} for 15 sediment profiles that were deeper than the 1964 layer. Sediment deposition rates were higher for the 1954 to 1964 period with a range of 0.31–3.50 cm year^{-1} with an average of 1.29 ± 1.04 cm year^{-1} for 12 profiles that were deeper than the 1954 layer. Considering the fact that on five of the sediment profiles depth to the 1954 layer could not be determined, this average rate is underestimated. These data indicate that sediment deposition in the flood plain has decreased since the 1950s. This is consistent with the changing land use pattern from cultivation to pasture that has occurred in the watershed (CAWR, 1986). Such a land use change would result in a landscape less susceptible to soil movement.

Soil profiles were described at flood-plain cross sections 1 through 4 during sampling on November 2001 (Tables 3–6). The soils are of the Blucher (Fluvaquentic Haploxerolls) soil series and are mapped as map unit BcA-Blucher fine sandy loam, overwash, 0% to 5% slopes. Soils were sampled to a

Table 7
Sediment deposition rates in the Stemple Creek flood plain calculated based on the depth to the 1964 and 1954 deposition layer determined using ^{137}Cs

Sample year and site number	Depth to 1964 layer (cm)	Depth to 1954 layer (cm)	Deposition rate 1964–2002 (cm year^{-1})	Deposition rate 1954–2002 (cm year^{-1})	Deposition rate 1954–1964 (cm year^{-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			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			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			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			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			0.75	0.69	0.85

[a] These values are under estimated because the sediment profile collected did not extend below the level where ^{137}Cs concentrations reached zero.

depth where the soils were abruptly massive and had a higher density than the overlying soil. This depth varied from 30 to 60 cm. Soil below this depth was assumed to be older sediments that would have supposedly been laid down prior to deposition of ^{137}Cs in 1954. However, sometimes our soil samples to this higher density layer were not deep enough to get soil below the deposition of ^{137}Cs. The presence of ^{137}Cs at these lower depths suggests that this massive, dense soil layer is relatively young. The dense soil layer may be massive, that is poorly aggregated, because this layer seldom dries enough to shrink and swell, which would be necessary to form blocky structure. The layer may be dense, and apparently compacted, because of the overburden of sediment and floodwater when saturated.

Average sediment deposition was higher on cross section 1 (reach 1, see Fig. 1) and cross section 4 (reach 4) than the other cross sections for the 1964 to 2002 period. Cross section 1 is in the large flood plain area in the upper end of the watershed. This is an area where extensive row crop agriculture had occurred and where grazing now dominates. The soil profile description (Table 3) shows a deep loam soil with slopes of less than 2%. Cross section 4 (Table 6) is a

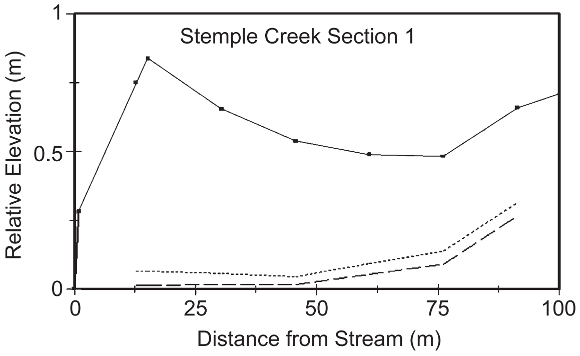

Fig. 4. Engineering surface survey of cross section 1 with depths to the 1964 and 1954 deposition layers based on ^{137}Cs measurements shown.

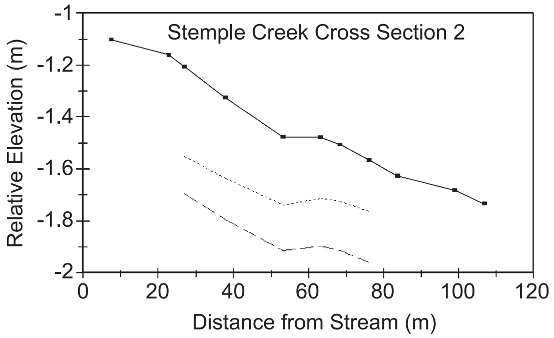

Fig. 5. Engineering surface survey of cross section 2 with depths to the 1964 and 1954 deposition layers based on ^{137}Cs measurements shown.

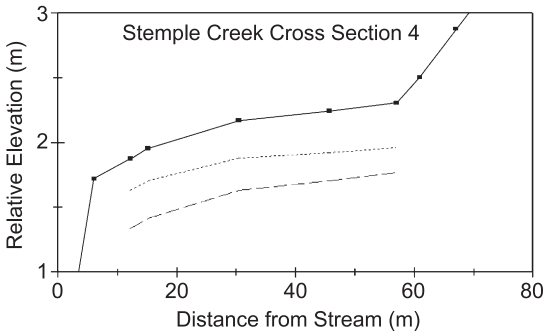

Fig. 7. Engineering surface survey of cross section 4 with depths to the 1964 and 1954 deposition layers based on ^{137}Cs measurements shown.

deep loamy sand with 2–5% slope. The other three cross sections had deposition rates that were 25% to 50% lower for the same time period.

Cross sections 3 and 4 had sediment deposition rates of 2 cm year^{-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 sections except cross section 1. Two of the four profiles collected for cross section 1 did not reach the 1954 layer, so if the two profiles that did reach the 1954 layer had been measured then cross section 1 would also probably have a higher deposition rate for the 1954 to 1964 time period. Again, this is consistent with the change from row crop agriculture to pasture in the watershed.

Relative surface elevations were measured for all cross sections. Examples of the measured cross sections for 2002 and the estimated cross sections for 1964 and 1954 based on the ^{137}Cs data for the cross sections are shown in Figs. 4–8. The cross-section surveys provided a basis for assuming that the average sediment deposition rates calculated from the individual soil profiles along the cross section are representative of the deposition rate for the entire cross section. Assuming that the cross sections that were sampled are representative of the reaches (Fig. 1), then total sediment deposited in the flood plain of Stemple Creek above reach 6 can be calculated for the 1954 to 1964, 1964 to 2002, and 1954 to 2002 time periods (Table 8).

Deposition rates in the flood plain ranged from 49 to 177 mt ha^{-1} year^{-1} for the 1964 to 2002 time period with a total of 129 mt ha^{-1} year^{-1} for the flood plain area above reach 6 (Fig. 1). Deposition rates were higher for the 1954 to 1964 time period, ranging from 94 to 223 mt ha^{-1} year^{-1}

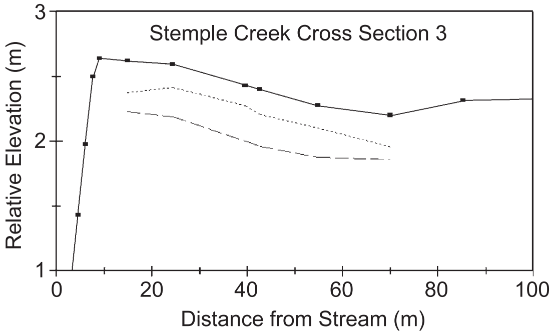

Fig. 6. Engineering surface survey of cross section 3 with depths to the 1964 and 1954 deposition layers based on ^{137}Cs measurements shown.

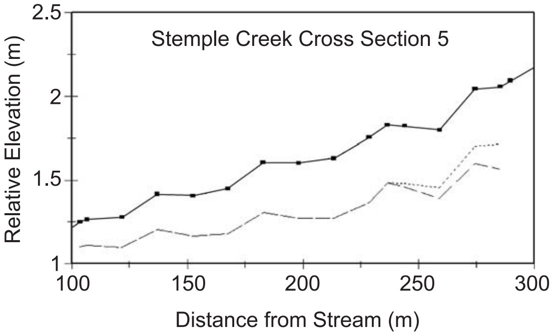

Fig. 8. Engineering surface survey of cross section 5 with depths to the 1964 and 1954 deposition layers based on ^{137}Cs measurements shown.

Table 8

Total estimated sediment deposition in Stemple Creek Watershed flood plain, 1954 to 2002

Reach[a]	Hectares flood plain	Deposition rate (cm year^{-1})	Bulk density (g cm^{-3})	Metric tons (year^{-1} reach^{-1})	Metric tons (reach^{-1})	Metric tons (year^{-1} ha^{-1})
Stemple Creek estimated flood plain deposition from 1964 to 2002						
1	539.1	1.217	1.46	95,788	3,639,958	177.7
2	97.3	0.614	1.31	7826	297,397	80.2
3	177.8	0.526	0.93	8697	330,509	48.9
4	52.6	1.053	0.99	5483	208,369	104.6
5	124.7	0.746	1.11	10,326	392,385	82.6
6[b]	96.7	Nd[c]	Nd	Nd	Nd	Nd
Total	1088.2			128,121	4,868,617	129.2
Stemple Creek estimated flood plain deposition from 1954 to 2002						
1	539.1	1.094	1.46	86,107	4,133,146	159.7
2	97.3	0.799	1.31	10,184	488,846	104.7
3	177.8	0.833	0.93	13,773	661,151	77.5
4	52.6	1.215	0.99	6326	303,696	120.3
5	124.7	0.694	1.11	9606	461,095	77.0
6[b]	96.7	Nd	Nd	Nd	Nd	Nd
Total	1088.2			125,999	6,047,934	127.1
Stemple Creek estimated flood plain deposition from 1954 to 1964						
1	539.1	0.830	1.46	65,328	653,281	121.2
2	97.3	1.500	1.31	19,119	191,195	196.5
3	177.8	2.000	0.93	33,071	330,708	186.0
4	52.6	2.250	0.99	11,717	117,167	222.8
5	124.7	0.850	1.11	11,765	117,654	94.4
6[b]	96.7	Nd	Nd	Nd	Nd	Nd
Total	1088.2			141,000	1,410,005	142.2

[a] See Fig. 1 for delineation of reaches in Stemple Creek Watershed.

[b] No samples were collected in reach 6.

[c] Nd—not determined.

with a total of 142 mt ha^{-1} year^{-1} for the flood plain area above reach 6 (Table 8). The pattern of deposition changed over time with reach 1 being greatest from 1964 to 2002 and reach 4 being highest from 1954 to 1964. Higher rates were found for reaches 2–5 for the 1954 to 1964 time period. Average deposition per unit area was 10% higher for the 1954 to 1964 period when compared with the 1964 to 2002 period.

Estimated total deposition in the flood plain area above reach 6 was 128 × 10^3 mt year^{-1} for the period between 1964 and 2002 and 141 × 10^3 mt year^{-1} for 1954 to 1964 (Table 8). Finney (2002), using the AGNPS model, estimated total erosion of 227 × 10^3 mt year^{-1}. Sediment delivered to the Bodega Bay was estimated to be 26 × 10^3 mt year^{-1} by the AGNPS model. Using our measured flood-plain deposition rates, 56% or 62% (1964–2002 or 1954–1964 time periods) of the AGNPS estimated erosion has been deposited in the flood plain. With 11% of the eroded material estimated by AGNPS being delivered to the end of the watershed, this leaves 34% or 27% of the AGNPS estimated erosion somewhere else in the watershed. AGNPS is designed to account for eroded material delivered to the edge of a landscape cell but does not account for eroded material that is redeposited within a landscape cell. Recent studies have indicated that significant amounts of eroded material are redeposited within the same field and never reach the edge of the field (Pennock and de Jong, 1990; Ritchie and McHenry, 1990; Kachanoski, 1993; Wallbrink and Murray, 1993; Lobb et al., 1995; Ritchie, 2000; He and Walling, 2003; Pennock, 2003; Ritchie and McCarty, 2003; Walling et al., 2003), which may account for the difference between our measurements and the AGNPS estimates.

Table 9
Sediment deposition and erosion rates for Stemple Creek Watershed and flood plain

	1964–2002		1954–1964	
Flood plain (this study)	128,121 mt year^{-1}		141,000 mt year^{-1}	
Bay	25,688[a] mt year^{-1}	46,263[b] mt year^{-1}	25,688[a] mt year^{-1}	46,263[b] mt year^{-1}
Total	153,809[a] mt year^{-1}	174,483[b] mt year^{-1}	166,688[a] mt year^{-1}	187,362[b] mt year^{-1}
Watershed area	13,348 ha		13,348 ha	
Sediment delivery ratio	0.17[a]	0.27	0.15[a]	0.25[b]
Erosion rates	11.52[a] mt ha^{-1} year^{-1}	13.07[b] mt ha^{-1} year^{-1}	12.49[a] mt ha^{-1} year^{-1}	14.04[b] mt ha^{-1} year^{-1}

[a] Based on Finney (2002) estimated sediment delivery of 25,688 mt year^{-1} into Bodega Bay.

[b] Based on NRCS (SCS, 1992) estimated delivery of 46,263 mt year^{-1} into Bodega Bay.

An earlier study by NRCS (SCS, 1992) estimated sediment delivery to Bodega Bay of 46×10^3 mt year^{-1}, indicating some uncertainty as to the sediment delivery ratio for the watershed. Other studies in northern California coastal watersheds have estimated sediment delivery ratios between 6% and 50% (Rice, 1996; Lewis, 2002). If we assume a higher sediment delivery ratio than was calculated by the AGNPS model then we would account for more of the eroded material from the watershed. However, we have no physical measurements other than the sediment deposited in the flood plain to use as a basis for determining a sediment delivery ratio.

Combining our measurements of flood-plain deposition and the AGNPS (Finney, 2002) estimated delivery to the end of the watershed give a total sediment deposition of 154×10^3 mt year^{-1} for the period between 1964 and 2002 (Table 9) and 167×10^3 mt year^{-1} for 1954 to 1964. An erosion rate of 11.5 mt ha^{-1} year^{-1} on the watershed would be needed to produce this amount of sediment for deposition for the 1964 to 2002 time period and 12.5 mt ha^{-1} year^{-1} for the 1954 to 1964 period. The AGNPS estimated erosion rates were 17.0 mt ha^{-1} year^{-1} for the watershed (Finney, 2002). These erosion rates appear to be reasonable for a watershed that has been in pasture (Table 2) for the last 40 years and are consistent with the T values between 2.2 and 11.2 mt ha^{-1} year^{-1} for the soil of the watershed (NRCS, 2002).

5. Conclusions

This study shows that the flood plains in the Stemple Creek watershed are a significant sink for the soils being eroded from the upland area. Deposition rates of 1 to 2 cm year^{-1} were measured for the period between 1954 and 2002. Such deposition rates are not unusual for flood plains (Ritchie et al., 1975; Owens et al., 1999; Walling, 1999; Walling et al., 1999; Terry et al., 2002). These rates account for more than 50% of the material estimated to be eroding from the watershed using the AGNPS model. Given the significance of the flood plain for trapping eroded material before it reaches the stream channel, Estero de San Antonio, or the Bay, efforts need to be made to manage these flood plain areas to insure that they do not change and become a significant source of eroded materials as improved management practices on the upland areas reduce sediment input.

Acknowledgements

The authors would like to thank the staff of the Petaluma NRCS Field Office for assistance in interfacing with the agricultural producers of Stemple Creek Watershed and the agricultural producers 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 go 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. Tom Share, GIS specialist in the NRCS office in Davis, CA, prepared the flood-plain map (Fig. 1). Thanks also go to R.A. Marston and two anonymous reviewers whose comments improved the manuscript.

References

California Department of Fish and Game Department (CAFG), 1977. The Natural Resources of Esteros Americano and de San Antonio. Report of the California Department of Fish and Game, Sacramento, CA.

California Department of Water Resources (CAWR), 1986. Land Use Maps of the Valley Ford, Two Rock, Cotati, Tomales, Point Reyes NE, and Petaluma U.S. Geological Survey Quadrangles. Report of the California Department of Water Resources, Sacramento, CA.

Finney, V., 2002. AGNPS Modeling of Stemple Creek Watershed, CA. NRCS Technical Report. California NRCS Watershed Planning Staff, 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., Walling, D.E., 2003. Testing distributed soil erosion and sediment delivery models using ^{137}Cs measurements. Hydrological Processes 17, 901–916.

Kachanoski, R.G., 1993. Estimating soil loss from changes in soil cesium-137. Canadian Journal of Soil Science 73, 515–526.

Kashiwagi, J.H., 1985. Soil Survey of Marin County, California. U.S. Department of Agriculture, Soil Conservation Service, Davis, CA.

Lewis, J., 2002. Quantifying recent erosion and sediment delivery using probability: a case study. Earth Surface Processes and Landforms 27, 559–572.

Lobb, D.A., Kachanoski, R.G., Miller, M.H., 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using ^{137}Cs as a tracer. Canadian Journal of Soil Science 75, 211–218.

Miller, V.C., 1972. Soil Survey of Sonoma County, California. U.S. Department of Agriculture, Forest Service and Soil Conservation Service, Davis, CA.

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

Owens, P.N., Walling, D.E., 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.

Pennock, D.J., 2003. Terrain attributes, landform segmentation, and soil redistribution. Soil and Tillage Research 69, 15–26.

Pennock, D.J., de Jong, E., 1990. Rates of soil redistribution associated with soil zones and slope classes in southern Saskatchewan. Canadian Journal of Soil Science 70, 325–334.

Prunuske-Chatham, 1994. Stemple Creek/Estero de San Antonio Watershed Enhancement Plan. California Water Resources Technical Report prepared by Prunuske-Chatham, Occidental, CA.

Rice, R.M., 1996. Sediment Delivery in the North Fork of Casper Creek—Final Report. U.S. Forest Service, PSW-95-CL-017, Berkeley, CA.

Ritchie, J.C., 2000. Combining ^{137}Cesium and topographic surveys for measuring soil erosion/deposition patterns in a rapidly accreting area. Acta Geologica Hispanica 35, 207–212.

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

Ritchie, J.C., 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., McHenry, J.R., Gill, A.C., 1973. Dating recent reservior sediments. Limnology and Oceanography 18, 255–264.

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

Soil Conservation Service (SCS), 1992. Stemple creek watershed erosion and sediment study, Marin and Sonoma Counties. SCS Technical Report. USDA Soil Conservation Service, Davis, CA.

Terry, J.P., Garimella, S., Kostaschuk, R.A., 2002. Rates of floodplain accretion in a tropical river system impacted by cyclones and large floods. Geomorphology 42, 171–182.

Travis, R.B., 1952. Geology of the Sebastopol Quadrangle, California. California Division of Mines Bulletin 162 (Sacramento, CA, 33 pp.).

Wallbrink, P.J., Murray, A.S., 1993. The use of fallout radionuclide as indicators of erosion processes. Hydrological Processes 7, 297–304.

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

Walling, D.E., He, Q., 1993. Use of cesium-137 as a tracer in the study of rates and patterns of floodplain sedimentation. International Association of Hydrological Sciences Special Publication 215, 319–328 (Wallingford, UK).

Walling, D.E., Owens, P.M., 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.

Walling, D.E., He, Q., 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.