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- 1 Quantifying sediment and particulate phosphorus accumulation in restored floodplain
- 2 wetlands using beryllium-7 as a tracer
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1 Abstract

2 Floodplain wetlands in agricultural river basins provide critical ecosystem services such as nutrient 3 retention, flood mitigation, carbon sequestration and ecological habitats and are a key component of 4 a nature-based solution approach to restoration. In the context of the global challenge to reducing 5 impact increasingly intensive food production on downstream ecosystems, restoration of wetlands 6 in river floodplains offers a practical means for downstream retention and mitigation of P flux from 7 upstream agricultural land. Data on short term, flood event related, accretion rates are, however, difficult to acquire via conventional monitoring yet such information is essential for restoration 8 9 planning and scenario testing. Here, we evaluate a promising approach that applies naturallyoccurring short-lived fallout radionuclide (FRN) ⁷Be as a tracer to quantify sediment and, by 10 association, particulate phosphorus retention rates in restored floodplain wetlands. Following a 11 series of major inundation events, a restored floodplain unit was sampled to determine ⁷Be 12 inventories of the floodplain relative to an undisturbed reference site. This was undertaken in 13 14 conjunction with direct measurement of sedimentation as an independent check of FRN results. Accretion rates up to 27 kg m⁻² were recorded using ⁷Be for recent deposition events compared to a 15 longer term annual average rate of ca. 6 kg m⁻² derived from ¹³⁷Cs measurements. While accretion 16 17 rates varied spatially and temporally, there was excellent coherence between FRN-based measurements and direct measurements once rigorous correction for particle size effects on tracer 18 19 properties had been undertaken. The study demonstrates the important contribution that FRN technology can make to support wetland management and restoration initiatives and the essential 20 21 need for a systems thinking approach across the soil-sediment continuum. Such decision support tools will become increasingly important in the 21st century with growing anthropogenic pressure 22 on aquatic ecosystems related to upstream food production, and implementation of more nature-23 24 based solutions such as restored wetlands to counteract these pressures.

- 1
- 2 Keywords: wetland restoration; nature-based solutions; floodplain sedimentation; fallout
- 3 radionuclides; systems thinking
- 4



6 Graphical abstract

1 1. Introduction

2 The sources, transport and destiny of suspended sediment and associated nutrients have been 3 intensively studied in many river basins worldwide (Walling, 1999). Riparian wetlands and 4 floodplains have been proven to act as important sinks for river sediments when water inundates the 5 floodplain and sedimentation of coarse and fine particles takes place (Mitch et al., 1979; Cooper et 6 al., 1987; Walling, 1999, Owens and Walling, 2003). Thus, several studies have shown the 7 importance of riparian wetlands and floodplains as sinks of river sediments (Kuenzler et al., 1980; 8 Lowrance et al., 1986; Walling and He, 1997; Brunet et al., 1994; Kronvang et al., 2002). 9 Restoration and management of wetlands at floodplain scales can be effective practices for retention and mitigation of P downstream of agricultural land (Kröger et al., 2012; Audet et al., 2020) but 10 there is limited information on shorter-term sedimentation dynamics related to recent restoration 11 initiatives targeting sediment and nutrients. This represents an important knowledge gap for 12 restoration planning in terms of both the approach taken and the extent of measures. Herein, it is 13 14 essential to take a whole-of-system approach along the soil-sediment continuum. 15 Prior studies have included many different techniques to measure sedimentation on floodplains such as use of bulk sediment traps (Mitch et al., 1979; Kronvang et al., 2002), sedimentation captured on 16 artificial Astroturf mats (Kronvang et al., 2009; Poulsen et al., 2014) and sediment budgets 17 (Novitzki, 1978; Brunet et al., 1994). Investigations have also used longer-lived fallout radionuclide 18 (FRN) tracer techniques such as ²¹⁰Pb dating (Kadlec and Robbins, 1984) and ¹³⁷Cs dating 19 20 (Johnston et al., 1984; Walling, 1999) that provide high resolution annual average estimates from retrospective sampling over periods of decades. This permits site selection for restoration to be 21 driven by current management questions but does not enable the benefits of recent management 22 actions to be assessed since detail is lost within long-term averaged data. 23

Here we demonstrate evidence of the efficacy of a natural tracer-based approach to close this 1 2 knowledge gap and support assessment of wetland restoration sites before and after implementation for sediment and nutrient retention. Short-lived cosmogenic beryllium-7 (⁷Be) with its half-life of 3 53.3 days offers potential to estimate short-term rates of sediment deposition, enabling assessment 4 5 of the effects of management practices. To date, limited studies have employed ⁷Be as a tracer to 6 measure sedimentation rates in geomorphic sink zones (Blake et al., 2002; Neubauer et al., 2002). 7 To the best of the authors' knowledge Blake et al. (2002) provide the only published example of its 8 use to assess overbank sedimentation on floodplains and the opportunity to provide critical post 9 restoration data on sediment input and storage has yet to be demonstrated. This contribution 10 demonstrates for the first time this important use of short-lived FRNs in a wetland restoration 11 context. Such information is becoming increasingly important with catchment restoration 12 programmes being undertaken to meet the challenges of food production versus environmental 13 regeneration and protection and in particular, the critical role of wetlands in management of river basin nutrient fluxes to the coastal zone. 14

15 Wetland restoration projects fit well into the nature-based solutions agenda (Albert et al., 2021) wherein allowing temporary floodplain inundations increases the water, sediment and nutrient 16 17 storage potential of the landscape. Thus, many river and wetland restoration programmes have been implemented in countries worldwide in order to increase biodiversity values (Mitch and Gosseling, 18 19 1993; Maltby et al., 1994), water storages (Verhoeven et al., 2008) and the use of wetlands and floodplains as sediment and nutrient sinks (Walling et al., 2003; Kronvang et al., 2009; Hoffmann et 20 21 al., 2011; Gonzalez-Sanchis et al., 2015; Hoffmann et al., 2020). In this context, information on 22 sediment accretion rates by restored wetland and floodplain units is required to support restoration decisions and could also assist in the development of Payment for Ecosystems Services systems 23 24 (e.g. Rouquette et al., 2009; Villa and Bernal, 2018). Moreover, information on sediment accretion

rates is important for the restored wetland and floodplain units functioning as a phosphorus sink and
 for considerations concerning the life span of the restored unit.

3

The Water Framework Directive (EC, 2000) demands that catchment management authorities of the European Union Member States improve the ecological status of surface waters by 2027.One of the main pressures that impact the ecological state of freshwaters are phosphorus emissions from point sources and diffuse sources (Kronvang et al., 2007). Therefore, in striving to meet the Directive's targets, a key focus for catchment managers is reducing P loadings introducing both source and transport management mitigation methods (Schoumanns et al., 2014).

10

To quantify the effect of river basin restoration measures via nature-based solutions, reliable and cost-effective post restoration monitoring methods are required. In the context of sediment and nutrient retention by wetlands, we propose that tracer tools can overcome limitations in traditional sediment trapping technology and can assist in the construction of sediment budgets to determine sediment and particulate phosphorus storage in restored riparian wetland.

16

Beryllium-7 tracer technology has been proposed as a valuable decision support tool within the context of catchment management and restoration (cf Mabit and Blake, 2019). The aim of this study was to demonstrate and validate the application of ⁷Be as a tracer for quantification of sediment and associated phosphorus accretion rates on restored floodplain wetlands. The work also aims to add rigour to the tracer conversion process to provide a transferable protocol that can effectively deliver a new decision support tool for management and restoration of floodplain and riparian wetlands.

1 2. Study site: The restored reach and floodplain of the River Odense, Denmark

In Denmark, River Basin Management Plans under the EU Water Framework Directive included an 2 3 extensive wetland restoration programme for reduction of nutrient transport to estuaries and a total 4 of 23,275 ha had been restored in 2020 (Hoffmann et al., 2020). Sediment associated nutrients and 5 contaminants remain a critical challenge in this region (Thodson et al., 2019). Moreover, a new 6 greening plan for Danish agriculture adopted in October 2021 to reach the 70% CO₂ emission 7 reduction goal in 2030 includes among other elements restoration of a total of 100,000 ha of 8 wetland areas in Denmark before 2030. 9 This study was carried out along a 6 km restored river and floodplain site along the River Odense on the island of Funen, Denmark (55°13' N, 10°15' W) (Fig. 1) during a period of floodplain 10 inundation over the re-wetted landscape. As well as acting to revitalise the natural hydraulic 11 12 interaction between a river and its floodplain, wetland restoration programmes have been included in two Danish Action Plans for Nutrient Reduction (Kronvang et al., 2005) and this site is an 13 innovative exemplar of this process with transferable relevance for other wetland restoration 14 15 schemes worldwide. The studied floodplain was restored in autumn 2003 by re-meandering and reducing the flow capacity of the formerly straightened river channel (Fig. 1). The restored river 16 floodplain site encompasses a total of 125 ha riparian areas that have been transformed from 17 intensively cultivated (ploughed) land to permanently grazed meadows that are periodically 18 19 inundated following restoration.

- 20
- 21

[insert Figure 1]

22

Figure 1: Overview map showing (a) River Odense location and (b) catchment area with (c) thestudy area where the river was re-meandered in autumn 2003 and (d) sample transects.

The catchment area upstream of the studied area (Fig. 1) is 254 km². Land use in the catchment at 2 3 the time of study was predominantly agriculture (ca. 65%). The area is underlain by moraine deposits from the last glaciation period (Weichsel) and primarily composed of clayey sandy (ca. 4 5 40%) and sandy clay soils (35%). Average annual long-term precipitation amounted to 727 mm and 6 average annual long-term runoff at the restored site amounted to 316 mm during the period 1989-2011. During the same period median minimum discharge was 1.2 m³ s⁻¹, median maximum 7 discharge was 3.3 m³ s⁻¹ and absolute maximum discharge was 22 m³ s⁻¹. The baseflow (BFI) index 8 for the River Odense is 0.67. 9

10

1

11 3. Experimental design and tracer method development

12

13 *3.1. Direct measurement of sediment deposition and P content on the restored floodplain surface*

To permit development and validation of the ⁷Be approach in restored floodplain wetlands, 14 deposition of sediment on the restored floodplain was assessed directly, during a period of storm 15 events that inundated the floodplain on several occasions (Fig. 2), using 1-3 artificial in excess of 80 16 17 pre-weighted Astroturf mats (Astroturf Textile Management Associates, Inc., Dalton, GA, USA) with a dimension of 15 x 15 cm installed at different distances along a randomly placed transect 18 19 from the river channel (1, 5.6, 10.7, 16.5, 23.8, 31.1, 40.8, 52.3, 71.8 and 101 m) between 2003 and 2012. The Astroturf mats, proven as an effective sediment trap elsewhere (e.g. Owens and Walling, 20 2002), were deployed in autumn (prior to the main rainy period) on the floodplain and fixed to the 21 22 grass meadow with four long spikes (one in each corner). After the flooding season each year, the Astroturf mats were retrieved from the meadow and brought to the laboratory in small plastic bags. 23

1	After recovery of the Astroturf mats, the amount of sediment on each mat was determined by pre-
2	weighing of the Astroturf mats and the newly collected Astroturf mats, and sediment was dried and
3	re-weighed at 60 °C for 24 h. The total mass of sediment on each Astroturf mat was then calculated
4	by subtracting the pre-weighed weight of the Astroturf mat. These samples were the most recent of
5	a longer term direct accretion measurement programme that has been in operation since floodplain
6	restoration (Poulsen et al., 2014). The content of total P in the sediment core was analyzed by
7	spectrophotometry according to the method described in Svendsen et al. (1993).
8	
9	[Insert Figure 2]
10	
11	Figure 2: flow regime of the restored river reach during the study period showing periods of
12	floodplain inundation, where flow (daily mean Q) exceed the bankfull flow (shown by red line), and
13	suspended sediment concentration (SCC)
14	
4 5	2.2 Some line for 7 B, and 137 C, to constitute the state of the sector of the state o
12	5.2. Sampling for Бе and «Cs to quantify seatment deposition on the restored floodplain surface
16	A key assumption for the use of ⁷ Be as a tracer is that following fallout, sorption to particles is rapid
17	and effectively irreversible over the timescales of interest (Taylor et al., 2013; Taylor et al., 2012a;
18	Mabit et al., 2008). By determining the difference in ⁷ Be areal activity (inventory) at a sampling
19	point and comparing the results with the activity at a reference baseline, from a site that has not
20	been inundated nor eroded, and considering the ⁷ Be activity in transported sediment, deposition

- rates can be estimated (Blake et al., 2002; Neubauer et al., 2002). A possible limit of using
- radioisotopes for estimating sediment accretion rates on floodplains is that ⁷Be activity is not evenly

distributed across sediment size fractions (Blake et al., 2009; Taylor et al., 2014; Mabit and Blake 2 2019), therefore, it is necessary to account for variation in ⁷Be activity in transported sediment size 3 fractions with respect to total bulk sediment activity. For example, ⁷Be typically displays 4 enrichment in fractions < 63 μ m (Blake et al., 2009; Taylor et al., 2014), implying that if these 5 fractions are representative of deposited material then failure to account for enrichment will lead to 6 overestimation of deposition rates.

7 The ⁷Be approach to determine short-term accretion rates requires quantification of (i) the ⁷Be inventory (Bq m⁻²) at a local reference site that has not been inundated by flood waters i.e. only 8 received aerial fallout inputs, (ii) the ⁷Be inventory on the inundated floodplain surface (Bq m⁻²) 9 which, after accretion, will be in excess of the reference inventory, (iii) the ⁷Be activity 10 concentration (Bq kg⁻¹) of the suspended sediment transported by the river channel during 11 inundation events (iv) the relationship between ⁷Be and specific surface area ($m^2 g^{-1}$) of the 12 sediment (Taylor et la., 2014) to permit effect of particle size enrichment to be accounted for and 13 14 (v) the specific surface area of the above sediment samples. Alongside, in the context of the restoration history, it is also useful to establish medium-term rates of accretion which can be 15 derived using ¹³⁷Cs inventories as described elsewhere (see Walling and He, 1997; Soster et al., 16 2007). 17

Short bulk sediment core (50 mm diameter) samples for ⁷Be analysis were taken from the floodplain of the River Odense during March 2011 and 2012 using simple cut drainpipe rings (30 mm depth). In addition, deep (0.5 m) section core samples and bulk sediment core samples for ¹³⁷Cs analysis (cf Walling and He, 1997) were collected in March 2011 following the winter inundation season. The purpose of these latter samples was to support assessment of longer term accretion rates since restoration to contextualise the contemporary processes observed.

During the period leading up to March 2012, an *in situ* suspended sediment sampler (Laubel et al., 1 2002) was installed in the channel to characterise the bulk ⁷Be concentration of suspended sediment 2 in transit during the inundation events. Note that this bulk signature of material entering the study 3 reach encapsulates any influence of suspended 'old' material from the bed and represents the ⁷Be 4 5 activity concentration of material delivered to the floodplain surface. Bulk sediment core samples 6 for ⁷Be analysis were retrieved from the floodplain in March 2012 to a depth of minimum 25 mm 7 (based on Blake et al., 2002) plus the depth of any freshly deposited sediment where observed. Five 8 multiple cores (diameter 54 mm) were taken at each site alongside the installed AstroTurf mats and 9 bulked to create a spatially integrated and representative sediment sample for ⁷Be analysis. All individual cores were taken to the same depth. In total, ten bulk core sample sets were collected at 10 11 different distances from the river channel reflecting the AstroTurf mat sites. Eleven bulk cores were 12 taken at the nearby reference site on the floodplain at a point that was above the height of all 13 inundations which occurred during the sampled winter inundation season.

14 For assessment of longer term accretion rates over the post restoration period (2003 - 2011), deeper cores for ¹³⁷Cs analysis were collected (cf Walling and He, 1997). To determine the depth profile, 15 one sediment core was collected 16 m from the river channel beside the AstroTurf mat site that had 16 17 been monitored during all winter seasons since the restoration in autumn 2003. The sediment core was retrieved using a Kajak coring device with a diameter of 5.4 cm equipped with a steel cap to 18 19 enable coring in sandy material (Svendsen and Kronvang, 1995). The sediment core was brought to the laboratory and sliced into thirty two 1 cm slices. Each slice was air dried at 40°C and weighed 20 21 prior to homogenisation with a pestle and mortar and passed through a 2 mm sieve. In addition, bulk sediment samples for ¹³⁷Cs analysis were retrieved to a depth of at least 30 cm along the full 22 transect, including all deposit material from the river on both the floodplain experiencing 23 24 inundations, where eight representative bulk sediment samples were retrieved. To determine the

reference inventory, 11 representative sediment bulk samples taken from a nearby level site above
 the height of all inundations since the 2003 river restoration.

3	All sediments were processed following the methods of Pennock and Appleby (2002). Samples
4	were air dried (< 40 $^{\circ}$ C) and disaggregated by hand using a pestle and mortar. The samples were
5	then sieved to remove large mineral debris > 2 mm, care being taken to ensure retention of organic
6	material. A subsample of the < 2 mm fraction was then oven dried at 105 °C to provide a dry-
7	weight correction value. The weights of both the > 2 mm and less than 2 mm fractions were
8	recorded and the material fraction < 2 mm was shipped to University of Plymouth Consolidated
9	Radioisotope Facility for gamma spectrometry analysis within 2 weeks of sampling.
10	Air-dried < 2 mm soil samples were packed into Marinelli beakers for analysis by gamma
11	spectrometry. All isotope analyses were carried out using a low background high purity germanium
12	(HPGe) gamma detector (GM50-83-LB-C-SMN-S Planar, Ortec, UK). Calibration was carried out
13	using standards of the same geometry as the experimental samples. Standards were prepared using
14	QCY58b-mixed standard solution (G E Healthcare, Amersham, UK) distributed in a mineral soil
15	matrix. Detector efficiency for ⁷ Be (477.6 keV) was determined by interpolation between the
16	efficiency values of ¹³⁷ Cs (661.7 keV) and ¹¹³ Sn (391.7 keV). Sample counts were corrected for
17	background emission, geometry efficiency and decay. All values were decay corrected to the time
18	of sampling and reported as activity (Bq kg ⁻¹). Laboratory analytical quality control procedures
19	were carried out in accordance with Wallbrink et al. (2002).

20

21 3.3. Converting ⁷Be and ¹³⁷Cs measurements into short- and medium-term accretion rates

The FRN inventories were converted to accretion rates based on the excess inventory (i.e. theamount of inventory greater than that measured at the non-depositional and non-eroding site)

method described by Walling and He (1997) for ¹³⁷Cs and Blake et al. (2002) for ⁷Be wherein the
latter was developed further to account for particle size selectivity and deposition across multiple
events.

4 *3.4 Examining the particle size association of*⁷*Be*

A key first step in the ⁷Be inventory conversion process was to determine how fluvial sorting would 5 affect the ⁷Be activity concentration of deposited sediment across the floodplain. Due to enrichment 6 7 of ⁷Be in finer sediment fractions with greater specific surface area, it was necessary to i) determine 8 the specific surface area, related to sediment size distribution, in deposited material and ii) estimate 9 ⁷Be enrichment factors for material at each sampled point on the floodplain surface. Estimating the relationship between ⁷Be and specific surface area in field material involves separating fractions 10 from a large mass of sediment to ensure a suitable mass for gamma detection. A more practical 11 approach for determining enrichment, using a low mass of sediment, was adopted here using stable 12 Be (⁹Be) following Taylor et al. (2012b). 13

A subsample of reference surface floodplain sediment was selected for the experiment and assumed 14 to be representative of suspended material. The sample was air dried, lightly disaggregated by hand 15 16 and sieved (< 2 mm) prior to being shaken with an equilibrating solution of stable ⁹Be based upon the method given in Taylor et al. (2012b). Stable ⁹Be solution was obtained by dissolving BeCl₂ salt 17 (99%) (Sigma Aldrich, UK) in ultra-pure water (Millipore Milli Q Plus 185 system), with solution 18 19 pH being buffered to 5.6 (natural rainwater pH) using NaOH. A 100 g subsample of the soil was rehydrated overnight in 100 mL ultrapure water after which 100 mL Be solution (10 mg L⁻¹) was 20 added to obtain a 5 mg L^{-1} concentration in the vessel. The sample was then placed on a reciprocal 21 shaker for 24 hours. This concentration enabled clear detection of Be sorption above natural 22

background levels. A 100 g soil sample was used to ensure that a suitable mass of material would
 be retrieved for each particle size fraction during the separation procedure.

3 Following shaking, the material was centrifuged at 3500 g for 20 minutes (Sorvall Legend RT, DJB 4 Labcare Ltd, UK) and an aliquot of the supernatant was sampled, acidified (pH < 2, HCl) and 5 retained for analysis to determine sorption from solution (> 98% Be sorption to soil from solution, 6 corrected for vessel sorption). The soil was then allowed to partially air dry in the open vessel to 7 enable the sample to be lightly disaggregated and homogenised by hand. A subsample of known 8 mass was taken to determine total Be concentration in the soil. Ultra-pure water was then added to 9 the remaining sample (to above surface) and the sample was left to rehydrate overnight. Following this, the vessel was placed in an ultrasonic bath (Laborette 17, Fritsch, Germany) for 20 minutes to 10 11 aid particle dispersion.

12 Next, the sample was added to a known volume of ultra-pure water in a settling column and thoroughly mixed into suspension. The sample was split by a combination of sieving and settling to 13 produce samples of decreasing particle size and hence increasing specific surface area, the key 14 15 measure used in the particle size correction process. All samples were dried at 40 °C. During each stage of the separation, a subsample of solution was filtered ($< 0.45 \,\mu$ m) and retained for analysis to 16 confirm that there was no loss of ⁹Be to the solution during the process. In addition to the 17 fractionation of the experimental sample, control samples, not mixed with ⁹Be solution, were 18 separated in the same manner to enable determination of background ⁹Be concentrations. 19

The air-dried sample fractions were then homogenised by hand and triplicate subsamples of known
mass were digested using microwave-assisted digestion (MARS 5 Accelerated Reaction System,
CEM Microwave Technology Ltd, UK) following Hassan et al. (2007). All samples were analysed
for Be concentration using ICP-OES (Varian 725 ES, Varian, Australia). Separate subsamples were

oven dried at 105 °C to allow moisture correction to be calculated. Further subsamples were
 oxidised using H₂O₂ to remove organic matter prior to particle size analysis using a Malvern
 Mastersizer 2000 with Hydro-G (Malvern Instruments Limited, Malvern, UK) according to ISO
 13320:2009.

5 The concentration of ⁹Be in the separated materials was then plotted against specific surface area 6 (SSA) as determined by laser granulometry, and the associated power function was then used to 7 estimate ⁷Be activity in field samples (following Taylor et al., 2014), taking into account its grain 8 size composition using SSA data from (i) the cores samples and (ii) surface sediment trap samples:

9
$$S(t) = S(m) \left[\frac{SSA(c)}{SSA(s)}\right]^{\nu}$$
(1)

10 where S(t) = the adjusted ⁷Be concentration in the deposited sediment fraction (mg kg⁻¹) and S(m) = 11 the measured ⁷Be concentration (mg kg⁻¹), SSA(c) = the standard specific surface area (m² g⁻¹) to 12 which the sample is adjusted (in this case the SSA of the suspended sediment collected from the 13 channel during the inundation events). SSA(s) is the SSA of the sediment and v is a parameter 14 reflecting the particle size selectivity of the sorption process (cf. He and Walling, 1996) which in 15 this case was derived from the ⁹Be:SSA relationship derived above.

16

17 3.5 Conversion model for ⁷Be floodplain inventories.

Event-based deposition estimates (R_d , kg m⁻²) based on ⁷Be inventory values (Bq m⁻²) were proposed by Blake et al. (2002) as follows:

$$R_d = \frac{I_{ref} - I_{dep}}{S}$$
(2)

where $I_{ref} = {}^{7}Be$ inventory obtained from the reference cores and fallout estimates (Bq m⁻²), $I_{dep} = {}^{7}Be$ inventory in the deposition zone (Bq m⁻²) and $S = {}^{7}Be$ the activity of the deposited sediment (Bq kg⁻¹).

4 In this case, however, deposition resulted from a series of inundation events and hence there was a 5 risk that inputs from events early in the study period might be underestimated due to radioactive decay of the associated ⁷Be signal. This issue has previously been raised in the context of erosion 6 estimates using ⁷Be by Walling et al. (2009) who developed a model to apportion erosion across 7 8 multiple events. In a similar fashion, a new deposition model was developed for this study which 9 accounted for additional ⁷Be inventory from fallout (F) as well as deposited sediment, while simultaneously accounting for radioactive decay across the study period to avoid underestimation of 10 deposition rates. 11

Here, a daily value of relative sediment loading *Sl* was estimated across the study period usingchannel-suspended sediment concentration data and calculated from:

$$Sl = \frac{Sl_d}{Sl_t}$$
(3)

where Sl_d = daily sediment loading and Sl_t = total sediment loading for the study period. Sediment loading was selected as it integrates suspended sediment concentration and water depth, via flow, both of which control potential accretion on the floodplain surface. The loading factor was only applied at times over overbank flow to ensure the correction process related to overbank events only.

Values of deposition rate *R* on each inundation day (*t*) are assumed to be proportional to the relative
sediment loading at times of overbank flow:

$$R(t) = Sl(t) \times C \tag{4}$$

2 where *C* represents a constant value.

Where deposition has occurred, the inventory in place at the end of each day, *I_{dep}* (*t*), can be
described as:

5
$$I_{dep}(t) = I_{dep}(t-1)e^{(-\lambda)} + F(t) + I_{gain}(t)$$
(5)

6 The increase in inventory at a sample point on day t (I_{gain} (t)) will reflect the depth of deposition
7 R(t) and the particle size corrected ⁷Be activity of the deposited sediment S(t):

8
$$I_{gain}(t) = Sl(t) \times C \times S(t)$$
(6)

9 A continuous mass balance for each study point was established and solved for C using an automatic optimization procedure. By applying the value of *C* obtained for an individual 10 11 sampling point to time series of *Sl(t)* for the study period, estimates of event deposition rates and the total deposition for the study period was calculated (cf Walling et al., 2009). The mass 12 13 balance required quantification of reference inventory losses and gains throughout the study period which was achieved by estimating rainfall activity concentrations using an iterative process to fit 14 the measured reference inventory. To explore the sensitivity of the conversion to particle size 15 16 correction factors, the specific surface area of the recently deposited sediment (from AstroTurf mats) and the bulk cores (25 mm depth) were used independently. 17

18

19 3.6 Conversion of ¹³⁷Cs inventories.

The excess inventory approach (cf. equation 1), i.e. excess relative to reference site, adopted for
 conversion of ¹³⁷Cs data followed the principles of Walling and He (1997) but in this case the

period to which the excess inventory applied was not from mid 1950s or 1963 but the time since 1 2 restoration i.e. 2003 to 2011. This meant that the measured reference inventory represented the inventory of the floodplain surface from 1963 up until 2003, i.e. the time of restoration, and it had 3 to be assumed that soil erosion on the drained and isolated, low gradient valley floor prior to 2003 4 5 was minimal. It was also noted that the valley floor had been cultivated prior to restoration giving a 6 uniform depth profile prior to sediment accumulation post restoration. For simplicity and given the short period of time since restoration, the surface concentration of 137 Cs was used in equation 1 to 7 8 avoid the need for particle size correction of contemporary suspended sediment activity concentrations, which, with variability in erosion and deposition dynamics over the 10 year period 9 10 are potentially not representative.

11

12 4. Results and discussion

13 4.1 Accretion rates since floodplain wetland restoration 2003 - 2011

14 4.1.1 Direct measurement of sediment accretion

15 The eight years of measured sediment deposition at the investigated transect with installed Astroturf mats since restoration (Fig. 3) reflected deposition being clearly highest within the first 30 m from 16 17 the river channel after which it declines rapidly. Accretion rates measured using AstroTurf mats annually from 2003/04 to 2011/12 (Fig. 4) show high temporal variability with highest accretion 18 19 rate measured during the first winter period following the re-meandering of the channel in autumn 2003 and no sediment accretion during the winter of 2008/09 (Fig. 4A). Sediment accretion rates 20 21 were in general highest during winters with highest flow conditions and highest number of flood 22 events such as the winter of 2006/2007 (Fig. 4B,C). The sediment accretion rates, ranging 0.1 to 100 kg m⁻², measured during the eight year period in this study (2003/04 to 2011/12) are comparable to 23

1	accretion rates found by Johnston et al. (1984) in a riparian forest levee (7.8 kg m ⁻² yr ⁻¹), Brunet et
2	al. (1994) for a single floodplain, riparian zone, France (28.9 kg m ⁻² yr ⁻¹), Tockner et al. (1999) for a
3	10 km stretch of floodplain along the River Danube, Austria (25 kg m ⁻² yr ⁻¹) and Walling (1999) for
4	21 floodplains in UK (0.4-12.2 kg m ⁻² yr ⁻¹).
5	
6	[insert Figure 3]
7	
8	Figure 3: Annual floodplain sedimentation rates directly measured using Astroturf mats along the
9	sample transect line for the period 2003/04 to 2011/12. Note that no floods took place during the
10	winter of 2008/09 and that grass mats were not installed during the winter of 2010/11.
11	
12	[insert Figure 4]
13	
14	Figure 4: (a) average sediment accretion rates, (b) runoff during the winter period October to March
15	(c) and number of flood events in each winter period for the period 2003/04 to 2011/12. Note that
16	no floods took place during the winter of 2008/09 and that grass mats were not installed during the
17	winter of 2010/11.
18	
19	4.1.2 Tracer-based assessment of medium-term sediment accretion rates to contextualise the
20	contemporary situation

1	The 137 Cs inventory at the non-inundated reference site on the River Odense floodplain was 1002 ±
2	129 Bq m ⁻² (n = 10). The sediment core taken at the central part of the transect showed measurable
3	¹³⁷ Cs activities to a depth of 35 cm (Fig. 5). The lack of a clear 1963 peak in activity concentration
4	relates to the fact that the land had been cultivated prior to restoration mixing the ¹³⁷ Cs inventory
5	associated with direct fallout throughout the ploughed layer of soil. Inundation after 2003
6	restoration led to a total inventory of 2070 \pm 408 Bq m ⁻² , 1068 Bq m ⁻² in excess of the reference.
7	Using the surface concentration of ¹³⁷ Cs to represent sediment inputs, the excess inventory equates
8	to 74 kg m ⁻² accretion over the 8 years since restoration in line with the direct measurements
9	(approximately 16 cm true depth given the low bulk density of the deposited sediment). Post
10	restoration accretion is therefore represented by the upper ca 8 g m ⁻² mass depth of the section core
11	(Figure 5) at which point a change in the character of total P loading of the deposited material is
12	observed (see section 4.3).
13	
14	[insert Figure 5]
15	
16	Figure 5: Depth distribution of ¹³⁷ Cs activity concentration and total P concentration at 16 m from
17	the river bank in the restored floodplain against mass depth (note there was no measurable activity

18

concentration below 16 g cm⁻²).

20 4.2. Quantifying short-term sediment deposition on floodplains using ⁷Be as tracer

21 The ⁷Be activity concentrations of the suspended sediment samples collected on 16/11/2011,

22 14/12/2011 and 12/01/2012 were 12.7, 65.3 and 32.6 Bq kg⁻¹, respectively. Variability in

1	concentration was likely related to (i) the developing catchment inventory during the study period
2	and (ii) variability in erosion process, e.g. sheetwash versus rill erosion, during the study period
3	(Walling et al., 1993; Wallbrink and Murray, 1993).
4	The importance of accounting for sorting effects when applying fallout radionuclides to quantify
5	sedimentation rates is illustrated in the relationship between ⁹ Be concentration and specific surface
6	area (SSA) (Fig. 6). While close to linear in this case, it is appropriate to represent this relationship
7	with a power function in accord with prior work (e.g. Blake et al., 2002; 2009; He and Walling,
8	1997) and equation 1. While the coarser fractions display similar SSA values, potentially the
9	influence of sediment aggregation and organic matter controls on density, there is a clear increase in
10	Be concentration with increasing SSA linked to the greater reactive surface area of the fine fraction.
11	[insert Figure 6]
12	
13	Figure 6: Relationship between specific surface area (as a proxy for overall particle size) and ⁹ Be in
14	the floodplain sediment to derive a correction factor for ⁷ Be inventory conversion to deposition
15	rates.
16	
17	It is also noteworthy that the ⁹ Be concentration had a strong positive correlation with clay content
18	($R^2 = 0.98$). This has important implications for the ⁷ Be approach in the context of differences in
19	SSA of suspended sediment and deposited sediment on the floodplain surface (Table 1a). In this
20	system, the suspended sediment captured in the channel (Table 1b) had an average SSA of 0.11 m^2
21	g ⁻¹ . This was notably lower to that of the sediment deposited on the AstroTurf mats which ranged
22	0.3 to 0.7 m ² g ⁻¹ and was linked to a greater proportion of clay sized material in the deposits. It is

23 possible that the material captured by the suspended sediment sampler underrepresented the clay

size fraction which further emphasises the importance of particle size correction to relate excess 1 inventory to the ⁷Be contributed by deposited sediment. It is also notable that the SSA of the bulk 2 surface cores collected was lower than that of the recent deposits. This could reflect (i) greater input 3 of coarse material in prior overbank events of higher magnitude or (ii) remobilisation of fines 4 5 within recently-deposited overbank-derived sediment over subsequent inundation events 6 (Greenwood et al., 2013). The difference in the grade of the bulk material and the surficial deposits from the most recent events has important implications for ⁷Be inventory conversion to accretion 7 8 rates.

At the time of sampling, the mean ⁷Be reference inventory measured at the non-inundated site was 9 640 ± 94 Bq m⁻² reflecting inputs from rainfall and radioactive decay over the study period (Figure 10 7). The ⁷Be inventory data showed higher inventories along the floodplain transect where sediment 11 deposition took place during winter 2011-2012 (Figure 8). The inventory conversion approaches 12 used to estimate sedimentation rates yielded a range of results (Table 2) wherein the extended time-13 14 series model with particle size correction based on the recent surficial deposit demonstrated excellent coherence with the Astroturf mat-derived accretion rates (note the site closest to the river 15 showed evidence of scour leading to an estimate of sediment loss) over the study period, i.e. event 16 scale deposition (Table 2, dataset D; Figure 8). Correction of the ⁷Be excess inventory for particle 17 size effects using the bulk core sediment properties gave results that markedly overestimated 18 19 sediment accretion rates (Table 2, dataset B). This emphasises the need to use sediment material representative of the specific storm events being studied for particle size correction procedures, 20 which presents a challenge when using the method as a retrospective investigative tool. 21

Table 1: (a) Particle size properties of the bulk cores collected for ⁷Be measurements and the
recently deposited material recovered from the AstroTurf mats (b) particle size properties of the
suspended sediment.

(a)	0 - 25 mm cores				Recent A	stroTurf	mat dep	osits
Sample location	SSA	Sand	Silt	Clay	SSA	Sand	Silt	Clay
Distance from channel (m)	$(m^2 g^{-1})$	(%)	(%)	(%)	$(m^2 g^{-1})$	(%)	(%)	(%)
1	0.02	92.1	7.9	0.0	n/a			
5.6	0.03	85.0	15.0	0.0	0.28	44.5	47.7	7.8
10.7	0.07	60.9	38.6	0.5	0.34	37.2	53.3	9.5
16.5	0.10	38.7	60.5	0.8	0.40	22.5	66.4	11.1
23.8	0.11	27.4	71.7	0.9	0.47	13.7	73.1	13.3
31.1	0.11	29.9	69.2	0.8	0.52	10.0	75.5	14.5
40.8	0.12	29.6	69.6	0.8	0.57	6.2	78.0	15.8
52.3	0.14	18.4	80.6	1.0	0.56	2.8	82.9	14.3
71.8	0.13	22.4	76.8	0.9	0.78	2.1	74.7	23.2
101	0.15	18.4	80.5	1.1	0.74	3.1	75.0	21.8

(b)				
Suspended Sediment	SSA	Sand	Silt	Clay
Date of collection	$(m^2 g^{-1})$	(%)	(%)	(%)
16/11/2011	0.14	26.9	71.9	1.2
14/12/2011	0.15	22.4	76.3	1.3
12/01/2012	0.06	71.4	28.2	0.3

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1		1	i	

linsert	Figure	71
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4

5 Figure 7: Rainfall and associated ⁷Be inventory development and decay at the non-inundated site in

[insert Figure 8]

6 months prior to overbank events studied.

7

8

9 Figure 8: Beryllium-7 inventory plotted against distance from the River Odense along the transect

10 deployed with Astroturf mats during winter 2011-2012.

- 1 Table 2: Sediment accretion rates estimated from ⁷Be measurements using both bulk and surficial sediment properties for particle size
- 2 correction.
- 3

Distance from channel (m)	Excess ⁷ Be inventory (Bq m ⁻²)	A: Deposition measured directly on AstroTurf mats (kg m ⁻²)	B: Deposition from ⁷ Be inventory with particle size correction based on bulk core properties (kg m ⁻²)	C: Deposition from ⁷ Be inventory with particle size correction based on surficial sediment properties (kg m ⁻²)	D: Deposition from ⁷ Be inventory as for A but using extended time series model (kg m ⁻²)	D: lower limit [*] (kg m ⁻²)	D: upper limit [*] (kg m ⁻²)
1	-301	-10.0	-6.1	n/a			
5.6	1285	11.7	26.2	10.0	11.0	8.5	13.8
10.7	3819	37.2	78.0	24.5	27.0	23.3	31.2
16.5	3684	15.6	75.2	19.7	21.7	18.7	25.2
23.8	2206	8.4	45.1	10.0	11.1	9.2	13.2
31.1	1634	5.9	33.4	6.8	7.5	6.1	9.2
40.8	1038	4.7	21.2	3.9	4.3	3.2	5.6
52.3	1346	3.5	27.5	5.2	5.7	4.5	7.2
71.8	481	1.4	9.8	1.3	1.4	0.8	2.2
101	489	1.0	10.0	1.4	1.5	0.9	2.3

5 * where upper and lower limit uncertainty is based on 95% confidence limits of the reference inventory estimate

[insert Figure 9]

2

Figure 9: Comparison of directly measured and ⁷Be-derived sedimentation rates (see Table 2 for
details).

5

6 *4.3 Storage of sediment associated phosphorus on restored floodplain wetlands.*

7 The deposition of sediment-associated phosphorus (P) was measured at each sampling point on the 8 floodplain as restoration of wetlands in river floodplains has been shown to be an effective practice 9 for retention and mitigation of P flux from upstream agricultural land (Kroger et al., 2013). The concentration of TP deposited on the floodplain showed a general increase with increasing distance 10 to the channel, a pattern which opposite to the sediment deposition amount (Fig. 3) which correlates 11 with particle size sorting effects. The deposited sediment near the channel bank edge (1 m) had a 12 measured average annual total P concentration amounting to 417±151 mg P kg DW⁻¹ which 13 increased to 1017±330 mg P kg DW⁻¹ at a distance of 5.5 m, 2309±372 mg P kg DW⁻¹ at a distance 14 of 16.5 m from the channel, 3554±455 mg P kg DW⁻¹ at a distance of 52 m from the channel and 15 6610±4918 mg P kg DW⁻¹ at a distance of 101 m from the channel during the period 2003/04-16 17 2011/12. The deposition of P varied both spatially and temporally according to the accretion patterns for sediment with an average deposition of 6.87 g P m⁻² yr⁻¹ (range: 0-13.5 g P m⁻² yr⁻¹) 18 during the investigated period (2003/04 to 2011/12). The range is comparable to upper values seen 19 elsewhere e.g. 1.46 g P m⁻² yr⁻¹ in eleven floodplains in USA by Johnston (1991), 12.7 g P m⁻² yr⁻¹ 20 in a French floodplain by Brunet and Astin (1998), 1.3-11.6 g P m⁻² yr⁻¹ in twenty-one floodplains 21 in UK (Walling, 1999). 22

The depth profile of total P in the sectioned core showed an increase in mass concentration from the point where ¹³⁷Cs data indicated post-restoration deposition to commence i.e. at ca 7.5 g m⁻² mass depth (approximately 16 cm true depth). The upper section total P concentration reaches a steady ca. 2.6 g kg⁻¹ which compares well to the mean average concentration measured in the deposited sediment amounting to 2309±372 mg P kg DW⁻¹ during the period 2003/04-2011/12.

6

7

8 This study demonstrates that restored floodplains and associated wetlands act as an important sink 9 for excess P in agricultural river basins and should be included as a part of catchment-wide initiatives to mitigate enhanced P flux due to agricultural land use. In the context of this global 10 11 challenge, the Danish Nature Agency decided in 2010 to include restored floodplains and associated wetlands, so-called 'P-wetlands', as a mitigation option for reducing P loads to lakes and estuaries 12 as part of the WFD River Basin Management Plan I (RBM I; Kronvang et al., 2011). Herein, 13 additional environmental geochemistry factors also need careful consideration. Phosphorus-14 mitigation wetlands are temporarily inundated floodplains that are re-established by re-meandering 15 16 the old channelized watercourse and lowering the discharge capacity. A technical guidance requires project areas to be screened for their content of iron and P before the floodplain areas are allowed to 17 be inundated due to the risk of releases of P from former fields having a high build-up of Fe-18 19 associated P in the soils following Fe dissolution under saturated conditions (Hoffmann et al., 2009; Kronvang et al., 2011). Utilization of restored floodplains and associated wetlands as sinks for 20 21 sediment P is also strongly in line with the need for development of novel technologies to capture and recycle P back to the circular economy to overcome P shortage in a world where this resource is 22

finite and to combat current dramatic losses in ecosystem biodiversity (Vaccari and Strigul, 2011;
 Elser and Bennett 2011; Steffen et al., 2015).

3

4 5. Synthesis and significance

A large range of functions and processes occur in naturally functioning floodplains that can affect
hydrology, water quality and biodiversity (Maltby et al., 1996). Generally these functions and
processes involve and rely on the import, transformation, export and/or storage of sediment,
sediment-associated chemicals and solutes during inundations of the floodplain with river water
(Malmon et al., 2002). Understanding sedimentation dynamics is essential to plan and evaluate the
success of floodplain and wetland restoration projects.

11 Attempts to assemble detailed information on contemporary rates of overbank sediment deposition on floodplains have to date faced many uncertainties and difficulties related to the inherent spatial 12 13 and temporal variability of such sedimentation and to the operational problems of studying an 14 inundated floodplain. Equally, because the depths of accretion involved are likely to be small, for 15 instance typically of the order of < 10 mm, reliable *in situ* measurements are difficult to obtain (Walling 1999). Furthermore, the amounts of deposition associated with individual events will vary 16 17 according to their magnitude and duration and other characteristics, including the suspended sediment concentration in the river which vary considerably both spatially and temporally (Walling 18 19 2000).

In this study, the labour-intensive collection of deposited material in conventional, direct
measurement sediment traps permitted validation of a new tracer tool that overcomes the above
critical limitations. Firstly, eight years of in situ measured sediment accretion rates on a floodplain
along the restored River Odense, Denmark was used as a mean of testing established use of ¹³⁷Cs as

a tracer for longer term sediment accumulation rates on restored floodplain wetlands. Secondly, in 1 2 situ measured sediment accretion rates during one winter period could be reliable mapped using a new application of ⁷Be as a sediment tracer. Fallout radionuclides have been shown to be a valuable 3 tool for assessing longer term (decadal) rates and patterns of accretion on rewetted land and the 4 5 innovative ⁷Be methodology here offers complementary evidence on the short term i.e. event to wet 6 season timescale. Critical methodological considerations emerged within this study. In particular, 7 the need for careful application of particle size correction procedures using deposited material at 8 each sampling point that is representative of the study period.

9 Our results from in situ measurements of sediment P storage on restored floodplains and associated
10 wetlands clearly demonstrate their use as an innovative technological tool to trap P from where it
11 may be later recovered and re-introduced into the P bio-cycle (Elser and Bennett, 2011; Steffen et
12 al., 2015).

With growing global interest in Payments for Ecosystem Services systems linked to nature-based
solutions and river basin restoration programmes (Vlachopoulou et al., 2014), reliable
methodologies to assess sedimentation rates and nutrient retention are required. The use of fallout
radionuclides to assess sedimentation patterns on floodplains permits the benefits of wetland
restoration programmes to be assessed. This in turn makes a valuable contribution to River Basin
Management Plans designed to combat excess P loading to lakes and estuaries as required by
environmental legislation across the world.

Floodplain wetland restoration is demonstrated to be an important means of mitigating excess
nutrient flux in agricultural and urban catchment systems. The tracer-based approach demonstrated
and tested here offers a powerful new decision support tool for floodplain and wetland restoration
planning. Floodplain rivers are a key strategic global resource in terms ecosystem service provision

(Tochner and Stanford, 2002) and decision support tools to support their conservation will become
 increasingly important in the 21st century with growing anthropogenic pressures on aquatic
 ecosystems (Albert et al., 2021).

4

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14	
15	References
16	
17	Albert C, Hack J, Schmidt S, Schroter B, (2021). Planning and governing nature-based solutions in
18	river landscapes: Concepts, cases, and insights. Ambio, 50:1405-1413
19	

20 Albert J.S. et al., (2020). Scientists' warning to humanity on the freshwater biodiversity crisis.

21 Ambio, 50:85-94

- Audet J, Zak D, Bidstrup J, Hoffmann CC 2020. Nitrogen and phosphorus retention in Danish 1 2 restored wetlands. Ambio, 49: 324-336
- 3 Blake, W.H., Wallbrink, P.J., Wilkinson, S.N., Humphreys, G.S., Doerr, S.H., Shakesby, R.A. and
- 4 Tomkins, K.M., 2009. Deriving hillslope sediment budgets in wildfire-affected forests using fallout

5 radionuclide tracers. Geomorphology 104, 105–116.

- 6 Blake, W.H., Walling, D.E. and He, Q., 2002. Using cosmogenic beryllium-7 as a tracer in 7 sediment budget investigations. Geografiska Annaler Series a-Physical Geography 84A, 89–102.
- 8 Brunet, R.C., Pinay, G., Gazelle, F. and Roques, L. 1994. Role of the floodplain and riparian zone
- 9 in suspended matter and nitrogen retention in the Adour River, south-west France. Regulated
- 10 Rivers: Research & Management 9, 55-63.

- 11 Brunet, R.C. and Astin, K. 1998. Variation in phosphorus flux during a hydrological season: the river Adour. Wat. Res. 32(3): 547-558. 12
- Cooper, J.R., Gilliam, J.W., Daniels, R.B. and Robarge, W.P., 1987. Riparian Areas as Filters for 13 Agricultural Sediment. Soil Science Society of America 51, 416-420.
- Elser J. and Bennett E. 2011. Phosphorus cycle: A broken biogeochemical cycle. Nature 478, 29-15 16 31. doi:10.1038/478029a
- Gonzalez-Sanchis M, Murillo J, Cabezas A, Vermaat JE, Comin FA, Garcia-Navarro P., 2015. 17
- Modelling sediment deposition and phosphorus retention in a river floodplain. Hydrological 18
- 19 Processes, 29: 384-394, DOI: 10.1002/hyp.10152

1	Greenwood P., Walling D.E., Quine TA. (2013): Using caesium-134 and cobalt-60 as tracers to
2	assess the remobilization of recently-deposited overbank-derived sediment on river floodplains over
3	subsequent inundation events. Earth Surface Processes and Landforms [DOI: 10.1002/esp.3442
4	Hassan, N.M., Rasmussen, P.E., Dabek-Zlotorzynska, E., Celo, V. and Chen, H., 2007. Analysis of
5	environmental samples using microwave-assisted acid digestion and inductively coupled plasma
6	mass spectrometry: Maximizing total element recoveries. Water, Air and Soil Pollution 178, 323-
7	334.
8	Hoffmann, C.C., Zak, D., Kronvang, B., Kjaergaard, C., Carstensen, MV & Audet, J 2020, 'An
9	overview of nutrient transport mitigation measures for improvement of water quality in Denmark',
10	Ecological Engineering, 155: 105863. https://doi.org/10.1016/j.ecoleng.2020.105863.
11	Hoffmann, C.C., Kronvang, B. and Audet, J., 2011. Restoration and monitoring of nutrient
12	buffering capacities in Danish riparian wetlands. Hydrobiologia 674, 5–24.
13	ISO 13320:2009. Particle size analysis-laser diffraction methods. International Organisation for
14	Standardisation, Geneva.
15	Johnston, C.A., Bubenzer, G.D., Lee, G.B., Madison, F.W. and McHenry, J.R., 1984. Nutrient
16	trapping by sediment deposition in a seasonally flooded lakeside wetland. Journal of Environmental
17	Quality 13(2), 283–290.
18	Johnston, C.A. 1991. Sediment and Nutrient Retention by Freshwater Wetlands: Effects on Surface
19	Water Quality. Critical Reviews in Environmental Control, 21 (5,6): 491-565.

Kadlec, R.H. and Robbins, J.A., 1984. Sedimentation and sediment accretion in Michigan coastal
wetlands (USA). Chemical Geology 44, 199–150.

R. Kröger, E.J. Dunne, J. Novak, K.W. King, E. McLellan, D.R. Smith, J. Strock, K. Boomer,
 Tomer, G.B. Noe, 2013. Downstream approaches to phosphorus management in agricultural
 landscapes: Regional applicability and use, Science of the Total Environment 442:263–274
 Kronvang, B., Falkum, Ø., Svendsen, L.M. and Laubel, A., 2002. Deposition of sediment and
 phosphorous during overbank flooding. Verhandlungen der Internationale Vereinigung der

6 Limnologie 28, 1–5.

7 Kronvang, B., Jeppesen, E., Conley, D., Søndergaard, M., Larsen, S.E., Ovesen, N.B. and

8 Carstensen, J., 2005. An analysis of pressure, state and ecological impacts of nutrients in Danish

9 streams, lakes and coastal waters and ecosystem responses to nutrient pollution reductions. Journal
10 of Hydrology 304, 274–288.

Kronvang, B., Vagstad, N., Behrendt, H., Bøgestrand, J. & Larsen, S.E. 2007. Phosphorus losses at
the catchment scale within Europe: an overview. Soil Use and Management 23, 104-116.

13 Kronvang, B., Hoffmann, C.C. and Dröge, R., 2009. Sediment deposition and net phosphorus

14 retention in a hydraulically restored lowland river-floodplain in Denmark: combining field studies

15 with laboratory experiments. Marine and Freshwater Research 60, 638–646.

Kuenzler, E.J, Mulholland, P.J. Yarbro, L.A. and Smock, L.A., 1980. Distributions and budgets of
carbon, phosphorus, iron and manganese in a floodplain swamp ecosystem. Report no. 157, Water

- 18 Resources Research Institute of the University of North Carolina.
- 19 Laubel, A., Kronvang, B., Fjorback, C. and Larsen, S.E., 2002. Time-integrated suspended
- 20 sediment sampling from a small lowland stream. Verhandlungen der Internationale Vereinigung für
- theoretische und angewandte Limnologie 28, 1420–1424.

1	Lowrance, R., Sharpe, J.K. and Sheridan, J.M., 1986. Long-term sediment deposition in the riparian
2	zone of a coastal plain watershed. Journal of Soil and Water Conservation 41, 266–271.
3	Mabit, L., Benmansour, M. and Walling, D.E., 2008. Comparative advantages and limitations of the
4	fallout radionuclides 137Cs, 210Pbex and 7Be for assessing soil erosion and sedimentation. Journal
5	of Environmental Radioactivity 99, 1799–1807.
6	Maltby, E., Hogan, D.V. and McInnes, R.J. 1996. Functional Analysis of European Wetland
7	Ecosystems - Phase I (FAEWE). Ecosystems Research Report No 18. European Commission
8	Directorate General Science, Research and Development. 448 pp. Brussels.
9	Maltby, E., Hogan, D.V., Immirzi, C.P., Tellam, J.H. and Van der Peijl, M., 1994. Building a new
10	approach to the investigation and assessment of wetland ecosystem functioning. Global Wetlands:
11	Old World and New (ed. W.J. Mitch). Elsevier, Amsterdam, pp. 637-658.
12	Mitch, W.J. and Gosselink, J.G., 1993. Wetlands, Van Nostrand Reinhold, New York, 722 p.
13	Malmon, Dunne T, Bren D, Renau SL., 2002. Predicting the Fate of Sediment and Pollutants in
14	River Floodplains. Environ. Sci. Technol., 2002, 36 (9), pp 2026–2032
15	DOI: 10.1021/es010509
16	Mitch, W.J., Dorge, G.L. and Wiemhoff, J.R., 1979. Ecosystem Dynamics and a Phosphorus
17	Budget of an Alluvial Swamp in Southern Illinois. Ecology 60, 1116–1124.
18	Neubauer, S.C., Anderson, I.C., Constantine and J.A., Kuehl, S.A., 2002. Sediment deposition and
19	accretion in a mid-Atlantic (USA) tidal freshwater marsh. Estuarine Coastal and Shelf Science 54,
20	713–727.
21	Novitzki, R.P., 1978. Hydrology of the Nevin Wetland near Madison, Wisconsin. U.S. Geological
22	Survey, Water Resources Investigation 78-48, USGS/WRI-78-48, 25 pp.

- 1 Pennock, D.J. and P. G. Appleby, P.G. (2002). Sample Processing. In: Zapata,
- 2 F. (ed.), Handbook for the assessment of soil erosion and sedimentation using
- 3 environmental radionuclides. Dordrecht, chapter 2: 15-40.
- 4 Poulsen, J.B., Hansen, F., Ovesen, N.B., Larsen, S.E. and Kronvang, B., 2014. Linking floodplain
- 5 hydraulics and sedimentation patterns along a restored river channel: River Odense, Denmark.
- 6 Ecological Engineering 66: 120-128.
- 7 Rouquette, J.R., Posthumus, H., Gowing, D.J.G., Tucker, G., Dawson, Q.L., Hess, T.M. and Morris,
- 8 J., 2009. Valuing nature-conservation interests on agricultural floodplains. Journal of Applied
- 9 Ecology 46, 289–296.
- 10 Schoumans, O., Chardon, W.J., Bechmann, M.E., Gascuel-Odoux, C., Hofman, G., Kronvang, B.,
- 11 Rubæk, G.H., Ulén, B., Dorioz, J.-M. 2014. Mitigation options to reduce phosphorus losses from
- 12 the agricultural sector and improve surface water quality: a review. Science of the Total
- 13 Environment 468-469: 1255-1266.
- 14 Soster, F.M., G. Matisoff, P.J. Whiting, W. Fornes, M. Ketterer, S. Szechenyi, 2007. Floodplain
- 15 sedimentation rates in an alpine watershed determined by radionuclide techniques. Earth Surf.
- 16 Process. Landforms 32, 2038-2051.
- 17 Steffen W., Richardson K., Rockström J., Cornell S. E., Fetzer I., Bennett E. M., Biggs R.,
- 18 Carpenter S. R., de Vries W., de Wit C. A., Folke C., Gerten D., Heinke J., Mace G. M., Persson L.
- 19 M., Ramanathan V., Reyers B., and Sörlin S. 2015. Planetary boundaries: Guiding human
- 20 development on a changing planet. Science 347. Published online 15 January 2015
- 21 [DOI:10.1126/science.1259855]

1	Svendsen, L.M., Rebsdorf, A. and Nørnberg, P. 1993. Comparison of methods for analysis of
2	organic and inorganic phosphorus in river sediment. Water Research 27(1): 77-83.
3	Svendsen, L.M. and Kronvang, B., 1995. Dynamics of phosphorus compounds in a lowland river
4	system: Importance of retention and non-point sources. Hydrological Processes 9, 119–142.
5	Taylor, A., Blake, W.H., Couldrick, L. and Keith-Roach, M.J., 2012a. Sorption behaviour of
6	beryllium-7 and implications for its use as a sediment tracer. Geoderma 187188, 16–23.
7	Taylor, A., Blake, W.H., Keith-Roach, M.J. & Couldrick, L., 2012b. Optimisation of beryllium-7
8	gamma analysis following BCR sequential extraction. Analytica Chimica Acta 720, 91–96.
9	Taylor A, Blake WH, Keith-Roach MJ, Mabit L. (2013). Assumptions and challenges in the use of
10	fallout beryllium-7as a soil and sediment tracer in river basins. Earth Science Reviews, 126:85-95,
11	doi: 10.1016/j.earscirev.2013.08.002
12	Taylor, A., Blake, W. H. & Keith-Roach, M. J. 2014. "Estimating Be-7 Association with Soil
13	Particle Size Fractions for Erosion and Deposition Modelling." Journal of Soils and Sediments 14
14	(11)
15	Thodsen, H., Rasmussen, J.J., Kronvang, B., Andersen, H.E., Nielsen, A., Larsen, S.E. (2019).
16	Suspended matter and associated contaminants in Danish streams: a national analysis. Journal of
17	Soils and Sediments, 19: 3068-3082
18	Tockner, K., Pennetzdorfer, D., Reiner, N., Schiemer, F. and Ward, J.V. 1999. Hydrological
19	connectivity and the exchange of organic matter and nutrients in a dynamic river-floodplain system
20	(Danube, Austria). Freshwater Biology, 41: 521-535.

- 1 Tockner K, Stanford J.A., 2002. Riverine flood plains: present state and future trends.
- 2 Environmental Conservation, 29: 308-330, DOI: 10.1017/S037689290200022X
- Vaccari D.A., Strigul N. 2011. Extrapolating phosphorus production to estimate resource reserves.
 Chemosphere 84, 792-797.
- Verhoeven, J.T.A., Soons, M.B., Janssen R. and Omtzigt, N., 2008. An operational landscape unit
 approach for identifying key landscape connections in wetland restoration. Journal of Applied
 Ecology 45, 1496–1503.
- 8 M. Vlachopoulou, D. Coughlin, D. Forrow, S. Kirk, P. Logan, N. Voulvoulis, 2013, The potential
- 9 of using the Ecosystem Approach in the implementation of the EU Water Framework Directive.
- 10 Science of the Total Environment 470–471: 684–694
- 11 Wallbrink, P. J. & Murray, A. S. (1993) The use of fallout radionuclides as indicators of erosion
- 12 processes. Hydrol. Processes, 297-304. Wallbrink, P.J., Walling, D.E. and He, Q., 2002.
- 13 Radionuclide measurement using HPGe gamma spectrometry. In: Zapata, F. (ed.), Handbook for
- 14 the Assessment of Soil Erosion and Sedimentation Using Environmental Radionuclides. Kluwer,
- 15 Dordrecht, pp. 67–96.
- 16 Walling, D.E., Woodward, J.C. & Nicholas, A.P. (1993). A multi-parameter approach to
- 17 fingerprinting suspended sediment sources. In: N.E. Peters, E. Hoehn, Ch. Leibundgut, N. Tase &
- 18 D.E. Walling (Eds.) Tracers in Hydrology (pp 329-337). IAHS Publ. No. 215. IAHS Press,
- 19 Wallingford
- Walling, D.E. and He, Q., 1997. Investigating spatial patterns of overbank sedimentation on river
 floodplains. Water, Air and Soil Pollution 99, 9–20.

- Walling, D.E., 1999. Linking land use, erosion and sediment yields in river basins. Hydrobiologia
 410, 223–240.
- 3 Walling, D.E., Owens, P.N., Carter, J., Leeks, G.J.L., Lewis, S., Meharg, A.A. and Wright, J., 2003.
- 4 Storage of sediment-associated nutrients and contaminants in river channel and floodplain systems.
- 5 Applied Geochemistry 18, 195–220.
- Walling, D.E., Schuller, P., Zhang, Y. and Iroume, A., 2009. Extending the timescale for using
 beryllium 7 measurements to document soil redistribution by erosion. Water Resources Research
 45, W02418, doi:10.1029/2008WR007143.
- 9 Windolf, J., Blicher-Mathiesen, G., Carstensen, J. and Kronvang, B., 2012. Changes in nitrogen
 10 loads to estuaries following implementation of governmental action plans in Denmark: A paired
 11 catchment and estuary approach for analysing regional responses. Environmental Science & Policy
 12 24, 24–33.
- 13