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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**

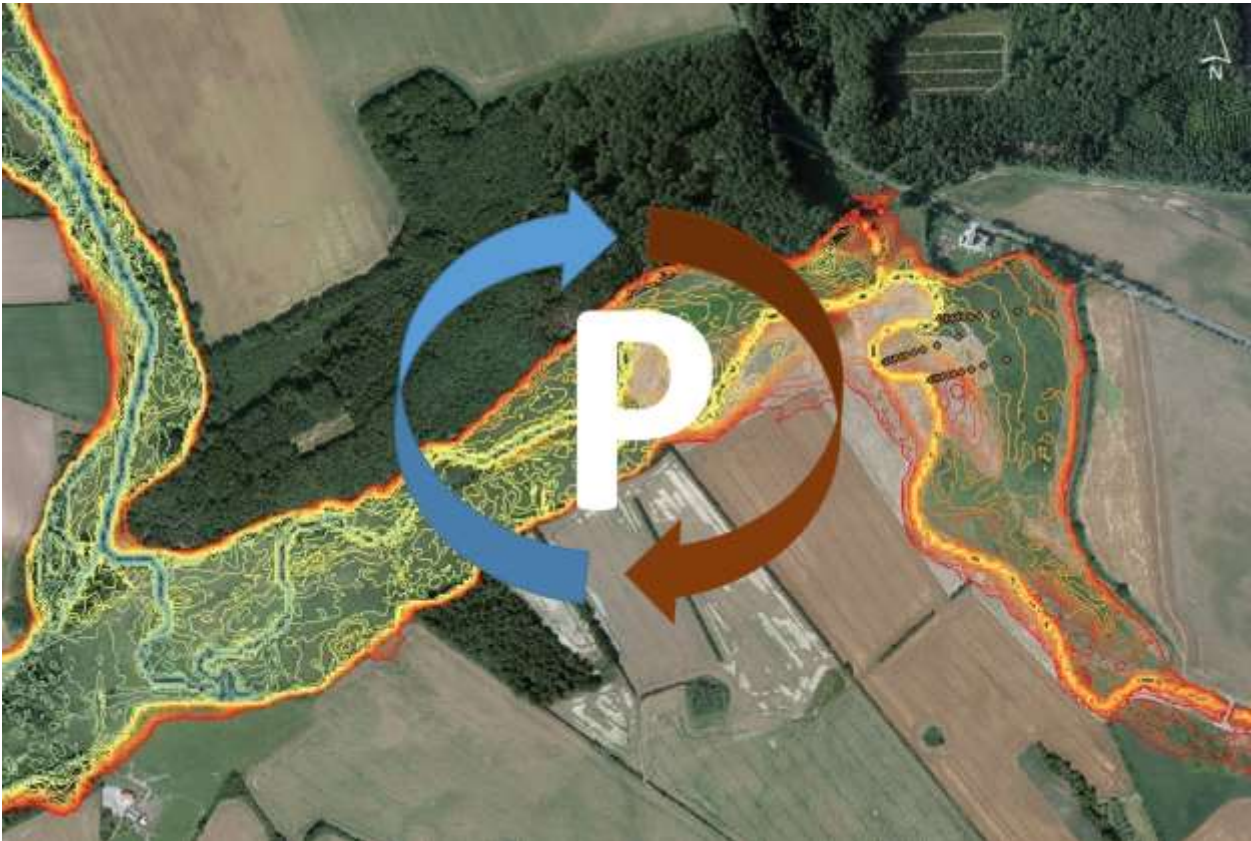
2 Floodplain wetlands in agricultural river basins provide critical ecosystem services such as nutrient
3 retention, flood mitigation, carbon sequestration and ecological habitats and are a key component of
4 a nature-based solution approach to restoration. In the context of the global challenge to reducing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



5

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
10 and mitigation of P downstream of agricultural land (Kröger et al., 2012; Audet et al., 2020) but
11 there is limited information on shorter-term sedimentation dynamics related to recent restoration
12 initiatives targeting sediment and nutrients. This represents an important knowledge gap for
13 restoration planning in terms of both the approach taken and the extent of measures. Herein, it is
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
16 as use of bulk sediment traps (Mitch et al., 1979; Kronvang et al., 2002), sedimentation captured on
17 artificial Astroturf mats (Kronvang et al., 2009; Poulsen et al., 2014) and sediment budgets
18 (Novitzki, 1978; Brunet et al., 1994). Investigations have also used longer-lived fallout radionuclide
19 (FRN) tracer techniques such as ^{210}Pb dating (Kadlec and Robbins, 1984) and ^{137}Cs dating
20 (Johnston et al., 1984; Walling, 1999) that provide high resolution annual average estimates from
21 retrospective sampling over periods of decades. This permits site selection for restoration to be
22 driven by current management questions but does not enable the benefits of recent management
23 actions to be assessed since detail is lost within long-term averaged data.

1 Here we demonstrate evidence of the efficacy of a natural tracer-based approach to close this
2 knowledge gap and support assessment of wetland restoration sites before and after implementation
3 for sediment and nutrient retention. Short-lived cosmogenic beryllium-7 (^7Be) with its half-life of
4 53.3 days offers potential to estimate short-term rates of sediment deposition, enabling assessment
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
14 basin nutrient fluxes to the coastal zone.

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

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

3

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

10

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

16

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

1

2

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

2 In Denmark, River Basin Management Plans under the EU Water Framework Directive included an
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
10 on the island of Funen, Denmark (55°13' N, 10°15' W) (Fig. 1) during a period of floodplain
11 inundation over the re-wetted landscape. As well as acting to revitalise the natural hydraulic
12 interaction between a river and its floodplain, wetland restoration programmes have been included
13 in two Danish Action Plans for Nutrient Reduction (Kronvang et al., 2005) and this site is an
14 innovative exemplar of this process with transferable relevance for other wetland restoration
15 schemes worldwide. The studied floodplain was restored in autumn 2003 by re-meandering and
16 reducing the flow capacity of the formerly straightened river channel (Fig. 1). The restored river
17 floodplain site encompasses a total of 125 ha riparian areas that have been transformed from
18 intensively cultivated (ploughed) land to permanently grazed meadows that are periodically
19 inundated following restoration.

20

21

[insert Figure 1]

22

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

1

2 The catchment area upstream of the studied area (Fig. 1) is 254 km². Land use in the catchment at
3 the time of study was predominantly agriculture (ca. 65%). The area is underlain by moraine
4 deposits from the last glaciation period (Weichsel) and primarily composed of clayey sandy (ca.
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-
7 2011. During the same period median minimum discharge was 1.2 m³ s⁻¹, median maximum
8 discharge was 3.3 m³ s⁻¹ and absolute maximum discharge was 22 m³ s⁻¹. The baseflow (BFI) index
9 for the River Odense is 0.67.

10

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*

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

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

15 *3.2. Sampling for ⁷Be and ¹³⁷Cs to quantify sediment deposition on the restored floodplain surface*

16 A key assumption for the use of ⁷Be 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 ⁷Be 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 ⁷Be activity in transported sediment, deposition
21 rates can be estimated (Blake et al., 2002; Neubauer et al., 2002). A possible limit of using
22 radioisotopes for estimating sediment accretion rates on floodplains is that ⁷Be activity is not evenly

1 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 $< 63 \mu\text{m}$ (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
8 inventory (Bq m^{-2}) at a local reference site that has not been inundated by flood waters i.e. only
9 received aerial fallout inputs, (ii) the ^7Be inventory on the inundated floodplain surface (Bq m^{-2})
10 which, after accretion, will be in excess of the reference inventory, (iii) the ^7Be activity
11 concentration (Bq kg^{-1}) of the suspended sediment transported by the river channel during
12 inundation events (iv) the relationship between ^7Be and specific surface area ($\text{m}^2 \text{g}^{-1}$) of the
13 sediment (Taylor et al., 2014) to permit effect of particle size enrichment to be accounted for and
14 (v) the specific surface area of the above sediment samples. Alongside, in the context of the
15 restoration history, it is also useful to establish medium-term rates of accretion which can be
16 derived using ^{137}Cs inventories as described elsewhere (see Walling and He, 1997; Soster et al.,
17 2007).

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

1 During the period leading up to March 2012, an *in situ* suspended sediment sampler (Laubel et al.,
2 2002) was installed in the channel to characterise the bulk ^7Be concentration of suspended sediment
3 in transit during the inundation events. Note that this bulk signature of material entering the study
4 reach encapsulates any influence of suspended ‘old’ material from the bed and represents the ^7Be
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
10 individual cores were taken to the same depth. In total, ten bulk core sample sets were collected at
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
15 cores for ^{137}Cs analysis were collected (cf Walling and He, 1997). To determine the depth profile,
16 one sediment core was collected 16 m from the river channel beside the AstroTurf mat site that had
17 been monitored during all winter seasons since the restoration in autumn 2003. The sediment core
18 was retrieved using a Kajak coring device with a diameter of 5.4 cm equipped with a steel cap to
19 enable coring in sandy material (Svendsen and Kronvang, 1995). The sediment core was brought to
20 the laboratory and sliced into thirty two 1 cm slices. Each slice was air dried at 40°C and weighed
21 prior to homogenisation with a pestle and mortar and passed through a 2 mm sieve. In addition,
22 bulk sediment samples for ^{137}Cs analysis were retrieved to a depth of at least 30 cm along the full
23 transect, including all deposit material from the river on both the floodplain experiencing
24 inundations, where eight representative bulk sediment samples were retrieved. To determine the

1 reference inventory, 11 representative sediment bulk samples taken from a nearby level site above
2 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 ($< 40\text{ }^{\circ}\text{C}$) and disaggregated by hand using a pestle and mortar. The samples were
5 then sieved to remove large mineral debris $> 2\text{ mm}$, care being taken to ensure retention of organic
6 material. A subsample of the $< 2\text{ mm}$ fraction was then oven dried at $105\text{ }^{\circ}\text{C}$ to provide a dry-
7 weight correction value. The weights of both the $> 2\text{ mm}$ and less than 2 mm fractions were
8 recorded and the material fraction $< 2\text{ mm}$ was shipped to University of Plymouth Consolidated
9 Radioisotope Facility for gamma spectrometry analysis within 2 weeks of sampling.

10 Air-dried $< 2\text{ mm}$ 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 ^7Be (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 ^{137}Cs measurements into short- and medium-term accretion rates*

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

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

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

5 A key first step in the ^7Be inventory conversion process was to determine how fluvial sorting would
6 affect the ^7Be activity concentration of deposited sediment across the floodplain. Due to enrichment
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
10 relationship between ^7Be and specific surface area in field material involves separating fractions
11 from a large mass of sediment to ensure a suitable mass for gamma detection. A more practical
12 approach for determining enrichment, using a low mass of sediment, was adopted here using stable
13 Be (^9Be) following Taylor et al. (2012b).

14 A subsample of reference surface floodplain sediment was selected for the experiment and assumed
15 to be representative of suspended material. The sample was air dried, lightly disaggregated by hand
16 and sieved ($< 2\text{ mm}$) prior to being shaken with an equilibrating solution of stable ^9Be based upon
17 the method given in Taylor et al. (2012b). Stable ^9Be solution was obtained by dissolving BeCl_2 salt
18 (99%) (Sigma Aldrich, UK) in ultra-pure water (Millipore Milli Q Plus 185 system), with solution
19 pH being buffered to 5.6 (natural rainwater pH) using NaOH. A 100 g subsample of the soil was
20 rehydrated overnight in 100 mL ultrapure water after which 100 mL Be solution (10 mg L^{-1}) was
21 added to obtain a 5 mg L^{-1} concentration in the vessel. The sample was then placed on a reciprocal
22 shaker for 24 hours. This concentration enabled clear detection of Be sorption above natural

1 background levels. A 100 g soil sample was used to ensure that a suitable mass of material would
2 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
10 this, the vessel was placed in an ultrasonic bath (Laborette 17, Fritsch, Germany) for 20 minutes to
11 aid particle dispersion.

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

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

1 oven dried at 105 °C to allow moisture correction to be calculated. Further subsamples were
2 oxidised using H₂O₂ to remove organic matter prior to particle size analysis using a Malvern
3 Mastersizer 2000 with Hydro-G (Malvern Instruments Limited, Malvern, UK) according to ISO
4 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:

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

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 ν 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.

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

$$20 \quad R_d = \frac{I_{ref} - I_{dep}}{S} \quad (2)$$

1 where I_{ref} = ^7Be inventory obtained from the reference cores and fallout estimates (Bq m^{-2}), I_{dep} =
2 ^7Be inventory in the deposition zone (Bq m^{-2}) and S = ^7Be the activity of the deposited sediment
3 (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
6 decay of the associated ^7Be signal. This issue has previously been raised in the context of erosion
7 estimates using ^7Be by Walling et al. (2009) who developed a model to apportion erosion across
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
10 simultaneously accounting for radioactive decay across the study period to avoid underestimation of
11 deposition rates.

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

$$14 \quad Sl = \frac{Sl_d}{Sl_t} \quad (3)$$

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

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

1
$$R(t) = Sl(t) \times C \quad (4)$$

2 where C represents a constant value.

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

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

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 ${}^7\text{Be}$ activity of the deposited sediment $S(t)$:

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

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

18

19 3.6 Conversion of ${}^{137}\text{Cs}$ inventories.

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

1 period to which the excess inventory applied was not from mid 1950s or 1963 but the time since
2 restoration i.e. 2003 to 2011. This meant that the measured reference inventory represented the
3 inventory of the floodplain surface from 1963 up until 2003, i.e. the time of restoration, and it had
4 to be assumed that soil erosion on the drained and isolated, low gradient valley floor prior to 2003
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
7 short period of time since restoration, the surface concentration of ^{137}Cs was used in equation 1 to
8 avoid the need for particle size correction of contemporary suspended sediment activity
9 concentrations, which, with variability in erosion and deposition dynamics over the 10 year period
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
16 mats since restoration (Fig. 3) reflected deposition being clearly highest within the first 30 m from
17 the river channel after which it declines rapidly. Accretion rates measured using AstroTurf mats
18 annually from 2003/04 to 2011/12 (Fig. 4) show high temporal variability with highest accretion
19 rate measured during the first winter period following the re-meandering of the channel in autumn
20 2003 and no sediment accretion during the winter of 2008/09 (Fig. 4A). Sediment accretion rates
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
23 kg m^{-2} , measured during the eight year period in this study (2003/04 to 2011/12) are comparable to

1 accretion rates found by Johnston et al. (1984) in a riparian forest levee ($7.8 \text{ kg m}^{-2} \text{ yr}^{-1}$), Brunet et
2 al. (1994) for a single floodplain, riparian zone, France ($28.9 \text{ kg m}^{-2} \text{ yr}^{-1}$), Tockner et al. (1999) for a
3 10 km stretch of floodplain along the River Danube, Austria ($25 \text{ kg m}^{-2} \text{ yr}^{-1}$) and Walling (1999) for
4 21 floodplains in UK ($0.4\text{-}12.2 \text{ kg m}^{-2} \text{ yr}^{-1}$).

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 $1002 \pm$
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 $2070 \pm 408 \text{ Bq m}^{-2}$, 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}).

19 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 ^9Be 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 ^9Be in
14 the floodplain sediment to derive a correction factor for ^7Be inventory conversion to deposition
15 rates.

16
17 It is also noteworthy that the ^9Be concentration had a strong positive correlation with clay content
18 ($R^2 = 0.98$). This has important implications for the ^7Be 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 $0.7 \text{ m}^2 \text{ g}^{-1}$ 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

1 size fraction which further emphasises the importance of particle size correction to relate excess
2 inventory to the ^7Be contributed by deposited sediment. It is also notable that the SSA of the bulk
3 surface cores collected was lower than that of the recent deposits. This could reflect (i) greater input
4 of coarse material in prior overbank events of higher magnitude or (ii) remobilisation of fines
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
7 from the most recent events has important implications for ^7Be inventory conversion to accretion
8 rates.

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

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

25

1

(a)

Sample location	0 - 25 mm cores				Recent AstroTurf mat deposits			
	SSA	Sand	Silt	Clay	SSA	Sand	Silt	Clay
<i>Distance from channel (m)</i>	(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
<i>Date of collection</i>	(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

2

3

[insert Figure 7]

4

5 Figure 7: Rainfall and associated ⁷Be inventory development and decay at the non-inundated site in
6 months prior to overbank events studied.

7

[insert Figure 8]

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)	<i>D: lower limit*</i> (kg m ⁻²)	<i>D: upper limit*</i> (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

4

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

1 [insert Figure 9]

2

3 Figure 9: Comparison of directly measured and ^7Be -derived sedimentation rates (see Table 2 for
4 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
10 concentration of TP deposited on the floodplain showed a general increase with increasing distance
11 to the channel, a pattern which opposite to the sediment deposition amount (Fig. 3) which correlates
12 with particle size sorting effects. The deposited sediment near the channel bank edge (1 m) had a
13 measured average annual total P concentration amounting to $417 \pm 151 \text{ mg P kg DW}^{-1}$ which
14 increased to $1017 \pm 330 \text{ mg P kg DW}^{-1}$ at a distance of 5.5 m, $2309 \pm 372 \text{ mg P kg DW}^{-1}$ at a distance
15 of 16.5 m from the channel, $3554 \pm 455 \text{ mg P kg DW}^{-1}$ at a distance of 52 m from the channel and
16 $6610 \pm 4918 \text{ mg P kg DW}^{-1}$ at a distance of 101 m from the channel during the period 2003/04-
17 2011/12. The deposition of P varied both spatially and temporally according to the accretion
18 patterns for sediment with an average deposition of $6.87 \text{ g P m}^{-2} \text{ yr}^{-1}$ (range: $0\text{-}13.5 \text{ g P m}^{-2} \text{ yr}^{-1}$)
19 during the investigated period (2003/04 to 2011/12). The range is comparable to upper values seen
20 elsewhere e.g. $1.46 \text{ g P m}^{-2} \text{ yr}^{-1}$ in eleven floodplains in USA by Johnston (1991), $12.7 \text{ g P m}^{-2} \text{ yr}^{-1}$
21 in a French floodplain by Brunet and Astin (1998), $1.3\text{-}11.6 \text{ g P m}^{-2} \text{ yr}^{-1}$ in twenty-one floodplains
22 in UK (Walling, 1999).

1 The depth profile of total P in the sectioned core showed an increase in mass concentration from the
2 point where ¹³⁷Cs data indicated post-restoration deposition to commence i.e. at ca 7.5 g m⁻² mass
3 depth (approximately 16 cm true depth). The upper section total P concentration reaches a steady
4 ca. 2.6 g kg⁻¹ which compares well to the mean average concentration measured in the deposited
5 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
10 initiatives to mitigate enhanced P flux due to agricultural land use. In the context of this global
11 challenge, the Danish Nature Agency decided in 2010 to include restored floodplains and associated
12 wetlands, so-called 'P-wetlands', as a mitigation option for reducing P loads to lakes and estuaries
13 as part of the WFD River Basin Management Plan I (RBM I; Kronvang et al., 2011). Herein,
14 additional environmental geochemistry factors also need careful consideration. Phosphorus-
15 mitigation wetlands are temporarily inundated floodplains that are re-established by re-meandering
16 the old channelized watercourse and lowering the discharge capacity. A technical guidance requires
17 project areas to be screened for their content of iron and P before the floodplain areas are allowed to
18 be inundated due to the risk of releases of P from former fields having a high build-up of Fe-
19 associated P in the soils following Fe dissolution under saturated conditions (Hoffmann et al., 2009;
20 Kronvang et al., 2011). Utilization of restored floodplains and associated wetlands as sinks for
21 sediment P is also strongly in line with the need for development of novel technologies to capture
22 and recycle P back to the circular economy to overcome P shortage in a world where this resource is

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

3

4 **5. Synthesis and significance**

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

11 Attempts to assemble detailed information on contemporary rates of overbank sediment deposition
12 on floodplains have to date faced many uncertainties and difficulties related to the inherent spatial
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
16 (Walling 1999). Furthermore, the amounts of deposition associated with individual events will vary
17 according to their magnitude and duration and other characteristics, including the suspended
18 sediment concentration in the river which vary considerably both spatially and temporally (Walling
19 2000).

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

1 a tracer for longer term sediment accumulation rates on restored floodplain wetlands. Secondly, in
2 situ measured sediment accretion rates during one winter period could be reliably mapped using a
3 new application of ^7Be as a sediment tracer. Fallout radionuclides have been shown to be a valuable
4 tool for assessing longer term (decadal) rates and patterns of accretion on rewetted land and the
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).

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

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

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

4

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14

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