Modeling sediment deposition and phosphorus retention in the Ebro floodplain

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Abstract

The present work is devoted to the validation and application of the Soluble Reactive Phosphorus (SRP) model proposed in a companion paper, to a real riparian system of the middle Ebro river floodplain. The model is coupled to a complete 2D shallow water flow numerical model with sediment deposition. The SRP uptake model is validated using data from three field experiments. The model predictions showed a good accuracy for SRP concentration, where the linear regressions between measured and calculated of the three experiments were significant ($r^2 \geq 0.62$; $p \leq 0.05$). The sedimentation model is validated using field data collected during 2 real flooding events within the same river reach, of 8 and 27 days of duration, respectively. The comparison between calculated and measured sediment deposition shows a significant ($p \leq 0.05$) linear regression ($r^2 = 0.97$ and slope not significantly different from the unit). Then, the complete model that includes flow dynamics, solute transport, SRP uptake, sedimentation and flow erosive potential estimation is used to simulate and analyze floodplain sediment deposition, morphological activity, river nutrient contribution and SRP uptake. According to this analysis, the main SRP uptake process appears to be the sediment sorption. The analysis also reveals a disequilibrium between erosion and sedimentation, where sediment deposition prevails over erosive processes. Finally, simulation results suggest the presence of a lateral gradient of hydrological connectivity that decreases with the distance to the river, and controls the floodplain river matter contribution.

Keywords: Nutrient retention, model validation, retention efficiency, sediment deposition, morphological activity, floodplain, numerical modeling.

1. Introduction

Floodplain sedimentation may well be the main phosphorus (P) retention mechanism during floods (Olde Venterink et al. [46]). The role of floodplains in the nutrient dynamics occurring in river corridors has been reduced due to large-scale and widespread hydro-morphological engineering for transport, agricultural irrigation, and hydropower generation (Tockner and Stanford [61]). At the same time, these corridors have become recognized as the most biodiverse ecosystems on earth, (Junk et al. [28], Tockner and Stanford [61]) and as places of potentially major damage during infrequent floods (Te Linde, or Aerts et al.). This has led to a re-appraisal of the significance of floodplains across Europe and beyond (Junk et al. [28], Asselman and Middelkoop [3], Heiler et al. [23], Ward et al. [65]) and to investments in their restoration (De Waal et al. [13], Brookes and Shields [5], Galat et al. [14], Thot et al. [60], Schiemer et al. [53], Simons et al. [55]).

Direct measurements of riparian zone sedimentation and sediment-associated pollutants within different geomorphological settings and climatic regions are still rare (Steiger and Gurnell [56]). Hence, the question of the degree to which these zones may buffer the downstream transfer of sediment remains largely unanswered (Steiger and Gurnell [56]), and other approaches are necessary. The hydraulic approach to analyze the interaction between main channel and floodplain flow might be suitable in this point. Sellin [54] and Rajaratnam and Ahmadi [51] investigated this interaction through experimental flume studies, and revealed boundary shear stress distributions and resulting flow structures in compound

23 channel sections with floodplains. Floodplains can be roughened so that the in-
24 fluence of differential roughness on flow structures between floodplain and main
25 channel and the lateral and vertical momentum transfer processes can be studied
26 (e.g. Pasche and Rouvee [50]). The results of such studies have shown that the
27 interaction between the main channel and floodplain flows is extremely complex
28 with the formation of various three-dimensional flow structures, such as large in-
29 terrelated vortices (cf. Knight and Shiono [29]). Hence, floodplain topography
30 and flow patterns are the key controlling parameters for both the conveyance loss
31 and sedimentation dynamics (Walling [63]).

32 Numerical modeling is a useful tool for the hydraulic approach. Nicholas and
33 Walling [42] combined numerical modeling with field observations and illustrated
34 that both approaches indicate the dominant role played by small-scale topographic
35 features in controlling suspended sediment transport and deposition processes on
36 floodplain surfaces. In the past decade, several 1D and 2D models have been de-
37 veloped to simulate patterns of sediment deposition on floodplains. Some of these
38 models are based on a finite-element approach (e.g. Stewart et al. [57]; Hardy
39 et al. [21]) and others on a finite-difference approach (e.g. [42], Nicholas and
40 Walling [43]; Middelkoop and Van der Perk [36]). Particle-tracking method is
41 also a used methodology that avoids the numerical diffusion produced by the con-
42 ventional Eulerian models Thonon et al. [59]. However, these simplified methods
43 that in most cases uncouple the hydrodynamics from the solid transport, are not
44 enough when dealing with real cases. Ignoring unsteady hydrodynamical effects
45 means that only a quasi-steady process over very slowly varying bed level can be

reasonably modeled, so that, the correct simulation of solid transport in rapidly varying flows containing shocks or discontinuities remains excluded. When solving real problems one is likely to encounter all sorts of situations, with a high probability that naive methods will compromise the quality and reliability of the solution. In that sense, complex models, based on a finite volume method, that make use of the Navier-Stokes equations seems to be the best option to represent the hydrodynamic interaction between water and land.

Therefore, complex numerical simulation that couples dissolved and suspended solute transport, flow erosive potential estimation and SRP uptake, is proposed as a floodplain analysis tool, capable of predicting the hydraulic and sediment interactions between land and river in different spatial-temporal scales. The flow simulation model was developed by Murillo et al. [38] and Murillo et al. [39] and validated in Gonzalez-Sanchis et al. [20], is coupled with the predictive SRP uptake model developed in companion paper 1 and applied in the present work to the Middle Ebro River floodplain.

First, the SRP uptake and sedimentation models are validated using field data. Then, the results are used to analyze the current sedimentation, dissolved phosphorus uptake and floodplain river nutrient contribution of the study site.

2. Objectives

The aim of the study is to validate and to apply in a real riparian system, the coupled model formed by SRP uptake sub-model developed in the companion paper and a 2D hydraulic model that includes sediment deposition and flow erosive

68 potential estimation. The steps followed are:

- 69 1. Validation of the sedimentation sub-model in a real riparian system.
- 70 2. Validation of the predictive dissolved phosphorus uptake sub-model in a
71 real riparian system.
- 72 3. Analysis of the current floodplain SRP uptake potential using the simulation
73 tool.
- 74 4. Analysis of the current sediment and dissolved phosphorus floodplain dy-
75 namics through the simulation tool.

76 **3. Description of the study area**

77 The study area is a reach in the Middle Ebro River in northeast Spain, included
78 in the Natural Reserve "Los Galachos" (see Figure 1). The Ebro River, 910 *km*
79 long, is the largest river in Spain. It has an annual discharge into the Mediterranean
80 Sea of $1.8E07\ m^3/y$ and is regulated by the presence of 170 dams and reservoirs
81 on the river basin. The study area forms a meander ($3.7\ Km^2$, river width: 110
82 *m* with one island and an oxbow lake) located downstream Zaragoza city. The
83 discharge, averaged over the years 1927 to 2003, within this reach is $230\ m^3/s$
84 and the surface elevation ranges from 175 *m* a.s.l. at the river channel to 185 *m*
85 a.s.l. at the base of the old river terrace. The flooded area by the 19 *yr* return period
86 flood ($3000\ m^3/s$, 1927 – 2003) is $3.7\ Km^2$, whereas only about 40 % of the area
87 is flooded by a river discharge of $1000\ m^3/s$ (0.37 *yr* return period, 1927 – 2003),
88 and only 10 % is flooded by a river discharge of $600\ m^3/s$ (0.14 *yr* return period,

1927 – 2003). The oxbow lake is connected with the river when the discharge reaches $1100\text{ m}^3/\text{s}$, and this occurs 1-3 times per year.

[Figure 1 about here.]

The study site receives the effluent of a Waste Water Treatment Plant (WWTP) located 1 *Km* upstream from the reach, with a maximum discharge of $3\text{ m}^3/\text{s}$. This WWTP treats 1200000 inhabitant-equivalents, where 1 inhabitant-equivalent is the biodegradable organic matter load equivalent to a BOD5 (i.e., biochemical oxygen demand) of 60 g/day of O_2 . The plant has activated sludge biological treatment as well as the technology to actively remove nitrogen (N) and phosphorus (P), where its legal effluent N and P concentrations limit is 10 mg-N/l and 1 mg-P/l , respectively.

4. Methods

The predictive SRP uptake model (equations 6 and 7 in the companion part) will be coupled to a 2D hydraulic model. The coupling will be validated by comparing the numerical results obtained from the complete model with the experimental field data by means of a linear regression analysis. Then, validation of the sedimentation sub-model will be performed by comparing the numerical results with the experimental field data obtained from Cabezas and Comín. [8] and Cabezas et al. [12].

After validation, the complete model will be applied in the study site. An analysis of the current floodplain erosive potential, sedimentation, SRP uptake and river nutrient contribution was carried out using the complete model.

111 *4.1. Field experimentation: experiments 21, 22 and 23*

112 Three sampling campaigns were developed at the study site, where both the
113 inlet and outlet river phosphorus concentration were characterized during 24h.
114 Two sampling stations, SS 1 and SS 2, were established at the river: SS 1 was lo-
115 cated 750m downstream the beginning of the domain, and SS 2 was located 1100m
116 downstream SS 1 (see figure 2). Samples were collected using two automatic sam-
117 plers (Sigma[®] SD900) and acid-washed (HCl 50 %) PP bottles (1 l) were located
118 at SS 1 and SS 2 respectively. The sampling interval was established in order to
119 sample the same mass water at SS 1 and SS 2, and was calculated by means of
120 hydraulic simulation using the the 2D hydraulic model. Samples were collected
121 every 20 – 25min, depending on the river discharge, during 24h. River discharge
122 values were given by a gauging station belonging to the Ebro River Basin Ad-
123 ministration (www.chebro.es) located approximately 12 km upstream the study
124 site.

125 [Figure 2 about here.]

126 Experiment 23 showed the highest river discharge, and was developed two
127 days after a flooding event of $1554\text{ m}^3/\text{s}$ peak discharge. The other experiments,
128 21 and 22, were developed under low and steady discharge, respectively.
129 Water samples were used to determine Soluble Reactive Phosphorus (SRP), total
130 nitrogen, alkalinity, pH, conductivity, anions and cations, Total Suspended Solids
131 (TSS), Suspended Particulate Inorganic Matter (SPIM), Suspended Particulate In-
132 organic Matter (SPIM), Total Dissolved Solids (TDS) and suspended chlorophyll.

133 *4.1.1. Water samples analysis*

134 Water samples were transported to the chemical laboratory in dark cool-boxes
135 and filtered through 0.45 μ m-pore size Whatman[®] GF/F glass-fiber filters. Sol-
136 uble reactive phosphorus, total nitrogen and alkalinity were analyzed within 24h.
137 The remaining samples were preserved frozen at -20° C. SRP was analyzed us-
138 ing Murphy and Riley [40] molybdenum blue colorimetric method. Total nitrogen
139 was analyzed by catalytic combustion at high temperature (850° C) using a Multi-
140 N/C 3100 analyzer (AnalytikJena[®]). Anions and cations were analyzed us-
141 ing ionic chromatograph (Methrom 861 Advanced compact IC) fitted with 100 μ l
142 sampling loop. Alkalinity of unfiltered water was estimated within 4 h of collec-
143 tion by a potentiometric automatic titration with H₂SO₄ 0.04 N APHA [2]. TSS
144 were determined by filtering samples through pre-combusted (450° C, 2 h) 0.45
145 μ m-pore size Whatman[®] GF/F glass-fiber filters, followed by drying filters at
146 60° C until a constant weight was reached. This filter was used then to determine
147 the SPIM by means of combustion (450° C, 4 h) followed by weighing. SPOM
148 was calculated as the difference between TSS and SPIM. TDS were determined
149 by weighing the residue after evaporating 25 ml of filtered water at 100° C APHA
150 [2]. Suspended Chlorophyll (a, b, c and d) was determined by filtering samples
151 through 0.45 μ m-pore size Whatman[®] GF/F glass-fiber filters, followed by 23
152 h of filter digestion in acetone 90 %, adsorption measurements in a spectropho-
153 tometer equipped with a 1 cm quartz cuvette and using the mixed phytoplankton
154 extinction coefficients Jeffrey and Humphrey [27].

155 4.2. Simulation model

156 The complete 2D hydraulic model developed by Murillo et al. [38] and Murillo
157 et al. [39], coupled with the flow erosive potential estimation, sediment transport
158 and dissolved phosphorus uptake equations proposed in the companion paper will
159 be used in the present paper.

160 4.2.1. Quantification of the groundwater contribution

161 Infiltration and exfiltration phenomena can be detected by means of the nat-
162 ural chemical tracers. Natural chemical tracers are water compounds naturally
163 present in rivers, biologically and chemically stable and do not undergo micro-
164 bial transformations and gaseous losses. There are several natural tracers, such
165 as stable isotopes, chloride, bromide, etc., where the most widely used are chlo-
166 ride and bromide. Both of them are present in the Ebro river waters, both surface
167 and groundwater, but with very different concentrations, where chloride is much
168 higher than bromide (mean molar ratio at surface water Cl:Br 3151 : 1). Chloride
169 shows higher concentrations in groundwater than in surface water (Cabezas et al.
170 [11]), whilst bromide remains more or less the same in both surface and ground-
171 water (unpublished data). Hence, chloride will be used as a natural tracer of the
172 exfiltration phenomenon, and it can be calculated as follows:

$$Q_{out} = Q_{in} + Q_{gw} \quad (1)$$

$$\frac{Q_{in}}{Q_{out}} = \frac{Cl_{in}}{Cl_{out}} \quad (2)$$

$$Q_{gw} = (1 - \frac{Cl_{out}}{Cl_{in}})Q_{in} \quad (3)$$

173 where Q_{in} and Q_{out} are the water discharge at the inlet and the outlet of the
 174 domain respectively, Cl_{in} and Cl_{out} are the chloride concentration at the inlet and
 175 the outlet of the domain respectively, and Q_{gw} is the groundwater discharge con-
 176 tribution.

177 The accuracy of the groundwater contribution estimation is evaluated using the
 178 field data from the three sampling campaigns.

179 4.3. Validation of the SRP uptake model

180 The predictive SRP uptake model was validated by comparing the numeri-
 181 cal results obtained from the complete model with the experimental field data by
 182 means of a linear regression analysis.

183 4.4. Validation of the sedimentation model

184 Validation was performed using the field data obtained by Cabezas and Comín.
 185 [8] and Cabezas et al. [12], where the sedimentation was registered in two zones
 186 within the study area. The registered flooding events whose peak discharge and
 187 duration were very different were simulated. The first study, Cabezas and Comín.
 188 [8], was carried out under a single flooding event of 8 days duration and 754.44
 189 m^3/s of peak discharge. The second study, Cabezas et al. [12], reached 2250 m^3/s
 190 and lasted 27 days. Inlet TSS was also registered during both flooding events, and
 191 therefore used as a boundary condition.

192 4.5. Model application

193 The full model is used to analyze the current floodplain SRP uptake potential
194 and sediment dynamics. The analysis of the current floodplain hydromorpholog-
195 ical dynamics developed by Gonzalez-Sanchis et al. [20] within the same study
196 area is used in this paper.

197 4.5.1. Evaluation of the floodplain SRP buffering potential

198 The total SRP buffering potential of the floodplain was analyzed by means of
199 the nutrient addition technique. However, since the floodplain is included into a
200 natural reserve, it was not possible to add any nutrient to the river. Hence, the
201 2D hydraulic model was used to simulate nutrient addition scenarios instead. The
202 addition of four SRP concentration: 1, 3, 5 and 10 *ppm*, was simulated using an
203 steady state injection of 3 m^3/s . The river discharge was also steady, and the eval-
204 uated discharges were: 500, 1000, 1500 and 2000 m^3/s .

205 The SRP addition impact into the different floodplain habitats was also analyzed.
206 For that purpose, the floodplain was characterized according to the different habi-
207 tats of interest, which are: Crops/pasture, adjacent riparian forest, remote riparian
208 forest, paleochannel, oxbow lake, constructed wetlands distant riparian forest and
209 main river channel (see Figure 1).

210 4.5.2. Analysis of the current floodplain nutrient and sediment dynamics

211 Four of the previous flooding events occurred in 2007, with peak discharges
212 of: 800, 900, 1169 and 2250 m^3/s were simulated (see Table 1). The highest
213 flooding event was greatly regulated by the Ebro River Basin Administration, and

214 its duration reached 27 days. Due to this regulation, three peak discharges could
215 be differentiated within the same flooding event: 1378, 1880 and 2250 m^3/s . To
216 reduce the simulation time consuming, this flooding event was considered as a
217 three different flooding events, whose peak discharges reached: 1378, 1880 and
218 2250 m^3/s . To analyze the simulation results the floodplain habitats classification
219 showed in Fig. 1 was used.

220 [Table 1 about here.]

221 Water samples from the four flooding events were collected twice a day in
222 each flooding event, using acid-washed (HCl 50 %) PP bottles (1.5 l) at SS 1 and
223 SS 2 respectively (see Fig. 2). Water samples were used to determine the inlet
224 discharge of: SRP, total nitrogen, alkalinity, pH, conductivity, anions and cations,
225 TSS, SPIM, SPIM and TDS. To analyze the simulation results the floodplain habi-
226 tats classification showed in Fig. 1 was used.

227 **5. Results**

228 *5.1. Physical, chemical, and biological river parameters*

229 Experiments were developed within the winter season, in November-January
230 on 2009-2010. During our observations, the discharge ranged between 119 – 577
231 m^3/s (Table 2).

232 [Table 2 about here.]

233 Ambient SRP concentrations were steady among and within the experiments,
 234 ranging from 0.031 to 0.050 mg/l^{-1} . The mean molar DIN:SRP ratio was 206 : 1.
 235 Ambient nutrient concentrations were higher than in most of the reported studies
 236 on streams (Hoellein et al. [24], Melody et al. [34], Newbold et al. [41], Mul-
 237 holland [37], [33], House et al. [25]), but nutrient concentration in fresh water
 238 ecosystems with high agricultural activity can be orders of magnitude higher than
 239 in undisturbed systems Melody et al. [34]. Moreover, the WWTP located 1Km
 240 upstream the domain could be increasing the nutrient river concentrations.

241 5.2. Soluble Reactive Phosphorus retention

242 The general net mass balance of SRP, using the three experiments, did not
 243 significantly differ from 0 ($4.0E - 5 \pm 3.2E - 5 mg/l$; $sig.0.20$), indicating neither
 244 SRP uptake or release. Experiment 15 showed a significant positive difference on
 245 the SRP mass balance ($1.4E - 3 \pm 1.7E - 3 mg/l$; $p(t-test) \leq 0.001$), while mass
 246 balances of experiments 21 and 22 were non significant (see Table 3). It suggests
 247 the presence of an SRP uptake process at experiment 23.

248 [Table 3 about here.]

249 The fact that we only observed significant SRP retention in experiment 23 is
 250 probably related to the size of the flood, inundating a long area with a correspond-
 251 ing reduction in flow velocity. Indeed, this is confirmed by a reduction in TSS.
 252 Furthermore, experiment 23 showed a significant release of Cl^{-} , Br^{-} and TDS
 253 (see Table 3) into the flowing water. This could be due to a groundwater con-
 254 tribution. In natural fresh water systems, such as the Ebro river, it is possible to

find the infiltration or the groundwater exfiltration phenomena, where surface water discharge and its chemical composition can be altered. Infiltration reduces the water discharge at the same rate as TDS, anions and cations, while TSS concentration increases. On the contrary, groundwater contribution could decrease TSS and TDS concentrations, and increase water discharge and anions and cations whose groundwater concentration are higher than at the surface water. Experiment 23 also showed a significant decrease of suspended and dissolved solids concentration (see Table 3), suggesting groundwater exfiltration as well.

In experiments 21 and 22 no change in chloride and bromide concentrations was observed. On the contrary, TSS decreased at experiment 21 and increased during experiment 22. Variation of TSS concentration could be due to sedimentation/erosion processes. During Experiment 21, the water discharge decreased from 136.2 to 118.5 m^3/s . This probably induced sediment deposition, and therefore, a reduction in TSS concentration. During experiment 22 flow increased instead, from 270 to 390 m^3/s , which probably generated an erosive process that increased the water column TSS content.

5.3. *Quantification of the groundwater contribution*

Equation 3 was applied to Experiment 23 to quantify the groundwater contribution. The estimation was $3.4 \pm 0.3 m^3/s$, and it increased the surface water discharge from 552.5 ± 3.0 to $555.8 \pm 3.1 m^3/s$. Hence, despite the proportional contribution of groundwater is limited (0.6%), a new mass balance calculation

277 correcting the outlet discharge is required.

278 The 2D hydraulic model was applied to simulate Experiment 23 including the
279 groundwater contribution as an inlet flow and Cl^- source. Then measured and
280 calculated Cl^- concentrations were compared (Table 5) to evaluate the accuracy
281 of eq. 3. Results showed an excellent agreement between measured and predicted
282 data ($r^2 \geq 0.9$; $p \leq 0.05$), whose slope and intercept did not significantly differ
283 from the unit and zero, respectively ($p \geq 0.5$).

284 New SRP mass balance was calculated in Experiment 23 using the groundwater
285 contribution to correct the outlet river discharge. The new mass balance was still
286 significant ($1E-03$; $p \leq 0.01 \text{ mg/l}$), suggesting the occurrence of SRP retention.

287 5.4. Validation of the sedimentation model

288 Validation of the sedimentation model was performed by comparing the sim-
289 ulated and the experimental sedimentation rate registered by Cabezas and Comín.
290 [8] and Cabezas et al. [12] (see Table 4 and Fig. 3). Table 4 shows the compar-
291 ison between simulated and observed sedimentation rate. Simulation results did
292 not significantly differ from the experimental data ($p \leq 0.09$). A general linear
293 regression between calculated and registered sedimentation rate shows the sig-
294 nificant agreement between both sedimentation rates ($r^2 = 0.97$; $p \leq 0.05$ and
295 $slope = 1.20$; $p \leq 0.05$), where the slope was not significantly different from
296 unity. Nevertheless, the intercept did significantly differ from zero, suggesting a
297 systematic sediment deposition underestimation.

298 [Table 4 about here.]

299 Simulated sedimentation corresponds sufficiently with observed quantities,
300 justifying further use of the model.

301 [Figure 3 about here.]

302 5.5. SRP uptake model validation

303 Validation of the reactive SRP uptake model was performed by comparing the
304 numerical results obtained from the complete 2D model with the experimental
305 field data. Model predictions were quite acceptable, where the linear regres-
306 sions between measured and calculated SRP concentration of the three experi-
307 ments were significant ($r^2 \geq 0.6$; $p \leq 0.05$) (see Table 5). Model predictions did
308 not introduce a systematic error, slopes and intercepts did not significantly differ
309 from unity and zero respectively ($p \geq 0.1$).

310

311 [Table 5 about here.]

312 The 2D unsteady hydraulic simulation model was capable of reproducing the
313 ambient SRP evolution at the middle Ebro river under three different river dis-
314 charges. Hence, although the river flow was unsteady, the model predicted the
315 SRP uptake with an acceptable accuracy.

316 5.6. Model application: Analysis of the present scenario

317 The complete 2D unsteady simulation model includes passive and reactive
318 dissolved solute transport, suspended solute transport, erosive potential and sus-

319 pended solute sedimentation. Using the complete model it is possible to repro-
320 duce erosion/sedimentation processes, hydrological connectivity, nutrient flood-
321 plain river contribution and SRP uptake, which are the main processes involved in
322 floodplain evolution. Therefore, the model can interpret and predict the floodplain
323 development, which is a useful tool in floodplain analysis, ecological restoration
324 and in water policy management.

325 Four flooding events registered during 2007, with peak discharges of 800, 900,
326 1169, and 2250 m^3/s were simulated. All of them are ordinary flooding events
327 with a recurrence period of: 0.21, 0.25, 0.4 and 3.4 *yr* respectively. The discharge
328 of SPOM, SPIM, SRP and TDS registered at each flooding event was included
329 into the simulations.

330 Results established that the study area is almost completely flooded with a return
331 period of 3.4 *yr*, while 40 % of the study area is flooded every year. Almost all
332 the yearly flooded area corresponds to the first 200 *m* from the river bank to the
333 floodplain, where the right bank is flooded more intensively than the left bank.
334 According to the results, the study area is almost completely flooded with a return
335 period of 3.4 *yr*, where almost 30 % of the study area is flooded every year (see
336 Fig. 4). The frequently flooded area is adjacent to the main channel, and mainly
337 corresponds to riparian forest.

338

339 [Figure 4 about here.]

340 *5.6.1. Analysis of present floodplain hydromorphological dynamics*

341 Gonzalez-Sanchis et al. [20] analyzed the erosive potential of six ordinary and
342 extraordinary flooding events, and pointed out the lack of hydromorphological ac-
343 tivity, where the highest erosive potential is only capable of eroding 1 % (12983
344 m^2) of the study area. Furthermore, this erosive phenomenon corresponds to an
345 extraordinary flooding event, of 18.7 yr recurrence period and 3000 m^3/s of river
346 discharge, and is restricted to river defenses and urban and agricultural construc-
347 tions. In agreement with these results, it can be stated that after a 2250 m^3/s river
348 discharge flooding event, the only significant geomorphological change that was
349 found in the study area was a gravel bar deposition that destroyed the artificial
350 secondary channel (Gonzalez-Sanchis et al. [19]).

351

352 *5.6.2. Sedimentation*

353 Simulation results show a spatially variable sediment deposition across the
354 flood plain, where the greater sediment quantities were deposited on those sur-
355 faces within close proximity to the river channel. Most of the sediment (80 %) is
356 deposited in the 30 % of the yearly flooded area, which corresponds to the first
357 200 m from the river to the floodplain (see Figs. 5, 6). In contrast, only 6 % of
358 the sediment is deposited in the remote parts of the floodplain, which are flooded
359 with 3.4 yr of recurrence period (1927-2010). The estimated yearly sediment
360 floodplain deposition is 0.08 Kg/m^2yr , corresponding to 252.7E03 Kg over the
361 full floodplain area.

362 [Figure 5 about here.]

363 [Figure 6 about here.]

364 The estimated floodplain deposition ranged from 0.02 to 0.27 Kg/m^2 (see
365 Table 6). This amounted to 48.8E03-818.3E03 Kg of sediment and constitutes
366 0.08-0.15 % of the total sediment input during the considered flooding events.
367 In general, the accumulation of sediment decreased with distance from the river
368 channel. The adjacent riparian forest receives in almost all cases more than 50 %
369 of the deposited sediment whilst remote riparian forest areas, located in the old
370 floodplain terrace, receive less than 10 % of the total rate (see Table 6 and Table
371 7). Agricultural fields and pasture areas also show an important sedimentation
372 rate, that increases with river discharge. When the corridor is almost completely
373 flooded ($2250 m^3/s$), sedimentation rate at crops and pasture is higher than at the
374 riparian forest (see Table 7).

375 [Table 6 about here.]

376 [Table 7 about here.]

377 5.6.3. *Ambient SRP uptake*

378 Simulation results estimated a high SRP uptake capacity, ranging from 0.06
379 to 0.25 Kg/m^2 . This amounts 179.4-76.5 Tn , and corresponds to 56-83 % of the
380 total SRP input. Similar to sediment deposition, SRP uptake decreased with dis-
381 tance from the river channel (see Fig. 7). The main SRP uptake takes place within
382 the main river channel and its adjacent areas whilst remote zones such as remote

383 riparian forest, the oxbow lake and the constructed wetlands hardly received SRP
 384 load. A significant linear regression ($r^2 = 0.59$; $p \leq 0.05$) between total sedi-
 385 ment deposition and SRP load in the selected habitats (see Figure 1) after the four
 386 flooding events show the positive correlation between both processes. Hence, the
 387 main sedimentation areas correspond to the highest SRP concentration zones, and
 388 therefore, to the highest SRP uptake zones. However, the river channel is an ex-
 389 ception, and its sedimentation and SRP concentration show a different pattern.
 390 Since the main channel registers the highest flow velocity, its sediment deposition
 391 is restricted to the river bank areas. Hence, if the main channel habitat is removed
 392 from the linear regression, the correlation coefficient improves from $r^2 = 0.59$
 393 to $r^2 = 0.94$ ($p \geq 0.95$), and confirms the correlation between sedimentation and
 394 SRP uptake.

395 [Figure 7 about here.]

396 5.6.4. River dissolved nutrient contribution to the floodplain

397 Dissolved nutrient was included in the simulation model as TDS, where no
 398 reaction term has been included. Therefore, floodplain dissolved nutrient contri-
 399 bution shows exactly the same pattern as hydrological connectivity. The calcu-
 400 lated yearly dissolved nutrient contribution to the adjacent riparian forest is 37%
 401 of the total river load, while the remote riparian forest appears not to receive any
 402 dissolved nutrient load during an ordinary flooding event.
 403 The calculated yearly TDS river contribution to the oxbow lake is 0.7% of the to-
 404 tal river load, but it increases to 3% when the river discharge reaches $2250 \text{ m}^3/\text{s}$.

405 In the same way, TDS contribution to remote riparian forest increases from 0 to
406 6% of the total load when the river discharge reaches $2000\text{ m}^3/\text{s}$.

407 **6. Discussion**

408 Results from the full simulation model highlight the same lack of hydro-
409 morphodynamism problem as many empirical studies have previously pointed out
410 at the same study site (i.e. Ollero [47], Ollero [48], Cabezas et al. [9], Cabezas
411 et al. [10], González et al. [17], Ollero [49], Magdaleno and Fernandez-Yuste
412 [31]). González et al. [17] confirm that maintenance of current hydrogeomor-
413 phological patterns will not produce disappearance of most of the existing forests
414 but will keep aging them, and new pioneer forests will be confined to smaller
415 and more dynamic areas (usually close to the main channel or in-channel areas).
416 Ollero [48] stated that the Ebro river, at the 'Natural Reserve Los Galachos', has
417 lost its geomorphic dynamics, and therefore, no more oxbow lakes will be pro-
418 vided. An aerial photograph of the same study area can be observed in Cabezas
419 et al. [9] and Cabezas et al. [10], where the authors pointed the presence of limited
420 morphodynamic activity since the last half of the twentieth century. This lack of
421 hydro-morphodynamism has also been reported by many authors as a response
422 of the river management (Marchand [32]; Heiler et al. [22]; Schiemer et al. [53];
423 Giller [16]; Nilsson et al. [44]; Reckendorfer et al. [52]), and it constitutes a gen-
424 eral loss of floodplain buffering potential (Junk et al. [28], Ward et al. [66], Bunn
425 and Arthington [7], Tockner and Stanford [61]).

426 The estimation specific processes, such as sediment deposition, is also compara-

427 ble to that reported by Cabezas and Comín. [8] and Cabezas et al. [12] at the same
428 study site, but also to those empirically registered at different floodplains. Thoms
429 et al. [58] reported a sedimentation rate of 0.001-1.94 Kg/m^2 in the floodplain
430 River-Murray. Steiger and Gurnell [56], observed a similar sedimentation rate in
431 the riparian zones of the Garonne river that ranged from 0.1 to 160.1 Kg/m^2 . Kro-
432 nvan et al. [30] registered an average sedimentation rate of 3.6, 6.6, 3.2 and 3.0
433 Kg/m^2 for the rivers Gjern, Brede, Odense and Skjern, respectively. The spatially
434 variable estimated distribution of the deposited sediment is also consistent with
435 those reported by Asselman and Middelkoop [3], Walling et al. [64], Middelkoop
436 and Asselman [35], Kronvan et al. [30], Thoms et al. [58] or Steiger and Gurnell
437 [56].

438 SRP uptake has not previously been studied at our study site, and our modeling
439 results can not be compared to local data. Nevertheless, a comparison to other
440 studies reveals a slightly higher SRP uptake of the middle Ebro river floodplain.
441 Bowes and House [4] observed a dissolved inorganic phosphorus retention of 58-
442 74 % during an overbank flooding. Van der Lee et al. [62] observed a phosphorus
443 adsorption that ranged from 50 to 70 % of the total phosphorus. Gelbrecht et al. [15]
444 reported an SRP net retention during an overbank flooding that ranged from 64 to
445 76 %. Our higher SRP uptake estimation is probably due to an overestimation of
446 the net SRP uptake. Since the model does not consider the SRP remobilisation,
447 net SRP uptake could be overestimated.

448 On the contrary, the strong correlation between SRP uptake and sediment de-
449 position is consistent with the results of Olde Venterink et al. [45], who found

450 that phosphorus uptake is largely influenced by the process of sedimentation. In
451 the same way, Bowes and House [4] found that the highest dissolved inorganic
452 phosphorus retention occurred under the highest suspended solids concentration.
453 Alexander et al. [1] found that nutrient retention increased with decreasing water
454 depth streams and rivers of the Mississippi catchment.

455 The model estimations reveal a strong correlation between hydrological connec-
456 tivity and the redistribution of organic and inorganic matter. The model suggest
457 the presence of a flood and nutrient gradient from the river to the floodplain (see
458 Fig. 6 for sedimentation lateral gradient), which provide, at least once a year,
459 nutrients and water to the first 200 m, whilst remote zones, such as the old river
460 terrace, have to wait 3 or 4 years. This gradient was also empirically reported by
461 Gonzalez et al. [18] within the same study site. In the same way, these results are
462 also consistent with those obtained by Kronvan et al. [30], who stated that approx-
463 imately half of the total calculated amount of retained sediment was deposited in
464 the near-channel area. Brunet et al. [6] also found that deposition of sediment was
465 50 times higher in the riparian zone (1050 m away from the river channel) than
466 further away from the river channel.

467 The exchange of nutrients, organic matter, inorganic sediments, organisms, seeds
468 and vegetative material as well as the flow velocities and scouring during floods
469 shapes the structure and functionality of a floodplain (Junk et al. [28], Asselman
470 and Middelkoop [3], Heiler et al. [23], Ward et al. [65]). In that sense, the lateral
471 gradient, restricted to the first 200 m of the floodplain, and the lack of impor-
472 tant erosive processes would lead to an static ecosystem with most of the habitats

473 disconnected from the river, an old riparian forest and a limited renovation rate
474 (Junk et al. [28], Hughes and S.B. [26]). Hence, the floodplain will lose part of
475 its functions such as flooding events mitigation, water quality improvement, wild
476 life refuge and recreational use (Junk et al. [28], Ward et al. [66], Tockner and
477 Stanford [61]).

478 7. Conclusions

479 The aim of the study was to validate and apply a predictive simulation model
480 that integrates flow dynamics, sediment transport and phosphorus uptake in dif-
481 ferent spatial-temporal scales and suitable for floodplain ecological restoration
482 studies. In this point, SRP uptake predictions were always significant ($p \leq 0.05$)
483 with an r^2 that ranges from 0.6 to 0.8. Sedimentation predictions were also signif-
484 icant ($p \leq 0.05$) and with an $r^2 = 0.99$. Hence, the validation shows the model as
485 an excellent tool capable of predicting flooding, sedimentation and SRP uptake.
486 Estimated sedimentation and SRP uptake shows a positive correlation between
487 both processes, and indicates the SRP sediment adsorption as the main SRP up-
488 take process during flooding events. The model estimates a high floodplain ambi-
489 ent SRP uptake, that ranged from 85.2 to 96.3 %.

490 The simulation estimates a sediment deposition rate that ranges from 0.02 to 0.27
491 Kg/m^2 . Most of this sediment is deposited within the river adjacent areas, whilst
492 the remote floodplain zones hardly receive sediment. The estimated SRP uptake
493 ranges from 0.06 to 0.25 Kg/m^2 , where most of it is uptaken within the river ad-
494 jacent areas as well as within the river itself.

495 The simulation of the current floodplain dynamics highlighted the same lack of
496 hydro-morphodynamism problem as many empirical studies has previously pointed
497 out at the same study site and at many other floodplains. In that sense, according
498 to the simulation results, the remote floodplain areas show a lack of river nutrient
499 contribution that could affect to the nutrient plant availability. On the other hand,
500 the concentration of sedimentation within the river adjacent areas, might acceler-
501 ate its vertical accretion. Therefore, to guarantee the floodplain functionality, a
502 restoration that increases the hydromorphological activity and recovers the shift-
503 ing mosaic of habitats is necessary.

504

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Figure 1: Left: location of the study site. Black line: limit of the computational domain. Right: Habitats within the study site. 1: Crops/pasture. 2: Adjacent riparian forest. 3: Remote riparian forest. 4: Paleochannel. 5: Oxbow lake. 6: Constructed wetlands. 7: Distant riparian forest. 8: Main river channel.

Figure 2: Location of the two sampling stations at the study site. Black dots: sampling stations SS 1 and SS 2, respectively.

Figure 3: Linear regression between measured and simulated sediment deposition. Presented are the regression equation and the confidence interval. Measured sediment deposition data are from Cabezas and Comín. [8] and Cabezas et al. [12].

Figure 4: Water depth under the peak discharge of each hydrograph: 400 (I), 800 (II), 900 (III) and 1169 (IV) and $225 \text{ m}^3/\text{s}$ (V) river discharge.

Figure 5: Simulated sedimentation at hydrographs II, III, IV and V.

Figure 6: Sediment deposition profile. Upper: profile location. Arrow indicates the profile direction. Lower: sedimentation profile at hydrographs II, III, IV and V. Brown line: profile of the terrain. Bars: sediment accumulation.

Figure 7: Simulated SRP concentration during the peak discharge of hydrographs II, III, VI and V.

Table 1: Simulated hydrographs. The return period is calculated within the period: 1927-2010.

Hydrograph	Peak discharge (m^3/s)	T (yr.)	Duration (days)
I	400	< 0.1	3
II	800	0.21	7
III	900	0.25	8
VI	1169	0.40	6
V	2250	3.4	27
VI	3000	18.7	

Table 2: Physical and chemical characteristics of the Ebro river (arithmetic mean $\pm$ SD). Concentration variables are expressed in mg/l except SRP and Chl-a, which are in $\mu\text{g/l}$.

Variable	Experiment 21	Experiment 22	Experiment 23
Discharge(m^3/s)	127.3 ± 1.38	323.85 ± 8.78	546.66 ± 4.0
Temp.($^{\circ}\text{C}$)	18.23 ± 3.61	18.33 ± 3.93	11.95 ± 4.95
pH	7.94 ± 0.01	8.12 ± 0.01	8.35 ± 0.05
Ca^+	141.44 ± 1.01	140.00 ± 3.14	116.33 ± 3.82
Cl^-	117.65 ± 6.13	96.36 ± 3.60	65.30 ± 0.54
DIN	2.23 ± 0.08	2.36 ± 0.13	2.52 ± 0.01
TDN	3.79 ± 0.02	3.20 ± 0.05	3.09 ± 0.02
SRP	0.04 ± 0.01	0.04 ± 0.01	0.04 ± 0.00
Chl-a	3.59 ± 0.31	3.24 ± 0.41	2.38 ± 0.18
SPOM	7.20 ± 0.60	7.14 ± 0.74	5.14 ± 0.32
TSS	36.68 ± 0.87	32.98 ± 11.70	30.14 ± 0.80
TDS	733.60 ± 9.66	648.00 ± 7.03	477.14 ± 4.77

Table 3: Mass balances as the difference between outflow and inflow concentration of the chemical water parameters at each experiment. Presented are $\Delta variable \pm SD$ where negative values indicates consume, and positive values indicates release. Values significantly different from 0 at $p \leq 0.05$ resultant from the t -test are printed in bold.

Variable	Experiment 21	Experiment 22	Experiment 23
pH	-5.6E-03 $\pm$ 5.0E-02	-0.03 $\pm$ 0.04	-4.30E-03 $\pm$ 2.10E-02
Ca ⁺	-3.2 $\pm$ 5.8	-15.4 $\pm$ 14.9	3.1 $\pm$ 10.2
Cl ⁻	8.4 $\pm$ 23.8;	3.2 $\pm$ 8.1	0.9 $\pm$ 2.2
Br ⁻	5.6E-03 $\pm$ 2.0E-02	2.0E-03 $\pm$ 9.0E-03	-3.4E-03 $\pm$ 5.0E-03
DIN	0.2 $\pm$ 0.5	0.1 $\pm$ 0.4	-0.2 $\pm$ 0.5
TDN	-1.6E-03 $\pm$ 5.2E-02	-5.1E-02 $\pm$ 0.13	-0.1 $\pm$ 0.1
SRP	1.5E-03 $\pm$ 4.1E-03	-0.6 $\pm$ 3.1	-1.3 $\pm$ 1.7
SPOM	-0.7 $\pm$ 1.4	-0.9 $\pm$ 3.3	0.05 $\pm$ 1.6
TSS	-0.9 $\pm$ 2.0	-2.3 $\pm$ 3.8	-4.8 $\pm$ 6.9
TDS	1.8 $\pm$ 38.6	7.6 $\pm$ 22.1	-7.6 $\pm$ 12.8

Table 4: Comparison of measured and calculated deposited sediment at sampling points (g/m^2). Presented are the p – value from the t – student comparison. SF and MP are the sampling locations.

Study	Location	Measured	Calculated	p – value	Calculated area ave age
Cabezas and Comín. [8]	SF	2330.7 ± 771.08	2970.1 ± 545	0.05	1282
Cabezas and Comín. [8]	MP	5987.41 ± 776.7	4607.15 ± 670.51	0.05	5853
Cabezas et al. [12]	SF	4180 ± 270	3202 ± 599	0.09	3878
Cabezas et al. [12]	MP	13490 ± 2190	11527 ± 2750	0.05	8995

Table 5: Comparison of measured and calculated phosphorus concentrations in successive simulated SRP addition experiments, using the new reactive formulation. Last row presents the comparison between measured and calculated Chloride concentration in experiment 23.

Experiment	df	R ²	Slope±SE	p_{slope}	Intercept±SE	$p_{intercept}$
21	21	0.62	0.84±0.14	0.2	0.01±0.01	0.2
22	21	0.67	1.05±0.15	1	0.00±0.01	1.0
23	20	0.76	0.85±0.10	0.1	0.01±0.00	0.1
23-Cl ⁻	20	0.94	1.01±0.05	0.5	-0.94±3.55	0.5

Table 6: Total simulated sediment and SRP retention during each hydrograph.

Hydrograph	Sediment deposition			SRP uptake		
	%	Tn	Kg/m^2	%	Tn	Kg/m^2
I	0.12	57.3	0.02	77	182.7	0.06
II	0.08	48.4	0.02	70	179.4	0.06
III	0.15	147.0	0.05	56	280.6	0.07
IV	0.02	818.3	0.27	83	765.5	0.25

Table 7: Simulated sediment deposition (Tn) at each considered habitat during hydrographs II, III, IV and V. RF: Riparian Forest.

Hydrograph	Crop/pasture	Adjacent RF	Distant RF	Paleochannel	Oxbow lake	Constructed wetlands	River channel	Remote RF
II	3.1	33.2	0.0	0.7	0.0	0.0	20.3	0.0
III	4.4	29.4	0.0	1.3	0.0	0.0	13.2	0.0
IV	39.9	76.9	0.0	5.6	0.7	0.0	23.8	0.2
V	480.2	206.1	11.8	24.8	18.7	0.3	60.7	15.6