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1 Combining Sediment Source Tracing Techniques with Traditional 2 Monitoring: The “Arvorezinha Catchment” Experience

3
4 Jean P. G. Minella^{1*}, Gustavo H. Merten², Alexandre Schlesner¹, Felipe Bernardi¹,
5 Cláudia A. P. de Barros³, Tales Tiecher³, Rafael Ramon⁴, Olivier Evrard⁵, Danilo
6 Rheinheimer dos Santos¹, José Miguel Reichert¹, Rutineia Tassi⁶

7
8 ¹ Department of Soils, Federal University of Santa Maria

9 ² Department of Civil Engineering, University of Minnesota-Duluth

10 ³ Department of Soil Science, Federal University of Rio Grande do Sul

11 ⁴ BASF SA, Environmental Fate - Regulatory Science Crop Protection

12 ⁵ Laboratoire des Sciences et de l'Environnement (LSCE – IPSL), Unité Mixte de
13 Recherche

14 ⁶ Department of Sanitary and Environmental Engineering, Federal University of Santa
15 Maria

16
17 *Corresponding Author: jean.minella@ufsm.br, UFSM, Roraima Av., n.1000, Santa
18 Maria, RS Postal Code 97105-900, Brazil

19 20 **Abstract**

21 To truly understand the hydrologic and erosive processes that occur at the catchment
22 scale regarding land use and soil management changes, intensive monitoring is required
23 over a long period. Variables such as precipitation, flow rate, and suspended sediment
24 concentration are the fundamentals needed to estimate sediment yield. However, in
25 order to shed more light on the effects of soil management changes on sediment yield,
26 traditional hydrologic monitoring techniques can be paired with sediment tracing to
27 identify sediment sources. In addition, mathematical models that predict erosion and
28 sediment yield can also help understand the dynamics of erosion and deposition
29 between the hillslope and stream channel. Given the above, this paper provides an
30 overview of almost 20 years of monitoring (2002–2021) in the Arvorezinha
31 experimental catchment (1.23 km²) located on the edge of the Brazilian meridional
32 plateau in southern Brazil, which is subject to extreme erosion due to a combination of
33 factors related to intensive agriculture and steep slopes. The catchment was selected as a

34 study site to evaluate the effects of land-use changes and soil conservation management
35 on hydrology and sediment yield. The text reviews the history of the study, synthesizes
36 the main results, and describes the evolution of the monitoring techniques used while
37 giving special attention to the fingerprinting approach. In addition, the article discusses
38 the importance of catchment-scale studies for teaching, generating technical-scientific
39 knowledge, and fostering collaboration between national and international research
40 groups.

41

42 **Keywords:** fingerprinting approach, soil conservation, sediment yield, soil erosion,
43 mathematical modeling, environmental monitoring.

44

45

46

47 **1. INTRODUCTION**

48 Understanding soil erosion processes at the catchment scale requires combining a broad
49 set of environmental analysis techniques. Measuring the spatial and temporal variability
50 of erosion controlling factors and monitoring response variables is a challenge that
51 requires long-term commitment and multidisciplinary efforts. Nonetheless, despite the
52 difficulties inherent in monitoring, experimental catchments are natural laboratories
53 with enormous potential for professional training, knowledge construction, and an
54 incomparable experience for enhancing learning and scientific interactions.

55

56 The continuous and gradual accumulation of information provided by long-term
57 monitoring leads to more robust data over time as it facilitates the coupling of
58 complementary approaches. This is especially important for improving our
59 understanding of hydrological and erosional processes at the catchment scale. Sediment
60 yield, for instance, is the result of the interaction of numerous processes that provide the
61 mobilization and transfer of sediment from the catchment's hillslopes to river channels.

62

63 The data acquired from technical-scientific interactions and studies of the soil profile on
64 the effects of erosion on the drainage network at the hillslope scale allow a better
65 understanding of the phenomena. Therefore, the results meet the different social,
66 environmental, and economic demands of scientific knowledge naturally associated
67 with the different components of the landscape. Experimental catchments also integrate
68 people contributing to the same objective, just as sediment yield from the catchment
69 outlet integrates all the catchment's hydrological processes.

70

71 In catchment research, hydrological monitoring is pivotal, as all other approaches rely
72 on it. Precipitation, runoff, and suspended sediment concentration monitoring describe
73 the erosion and sedimentation processes based on their behavior during rainfall events.
74 However, traditional monitoring alone may be insufficient to understand the
75 mechanisms of sediment mobilization and its transfer from catchment hillslopes to the
76 river channel (Beven et al., 2005; Aulenbach et al., 2021; Fenicia & McDonnell, 2022).
77 The relationships between processes observed on the catchment hillslopes and in the
78 river channel are influenced by complex water and sediment transfer concepts, such as
79 connectivity and cumulative effects (Keesstra et al., 2020; Ziemer et al., 1991; Puttock
80 et al., 2013).

81

82 Understanding the erosion processes in the catchment based on the behavior of
83 sediment yield requires understanding the mechanisms that connect the river channel
84 and catchment hillslopes (Walling, 1983, 1999; Foster et al., 2022). In this sense,
85 creating and developing a method for identifying sediment sources, which is known as
86 the multi-parameter fingerprinting approach and the sediment fingerprinting technique,
87 has provided enormous advances in our knowledge of the existing relationships between
88 erosion processes on hillslopes and the sediment yield monitored in rivers (Walling et
89 al., 2001; Walling, 2005, 2013; Collins et al., 2020). The sediment fingerprinting
90 technique has established a new quality in research on sediment yield, providing further
91 information on the origins of the sediments mobilized on the catchment hillslopes and
92 the material exported from the catchment. This information can furnish numerous
93 technical and scientific advancement opportunities in soil and water management and
94 mathematical modeling.

95

96 In order to demonstrate the importance of coupling conventional monitoring in
97 identifying sediment sources through the fingerprinting technique, this article reports
98 the experience of hydrological and erosion studies conducted in the Arvorezinha
99 experimental catchment in southern Brazil. The text provides novel data on the
100 evolution of monitoring-supported sediment transport modeling, emphasizing sediment
101 tracing methods' contribution to better understanding erosion processes at the
102 catchment scale. In addition, this study revisits two decades of scientific production,
103 demonstrating the importance of experimental collections at the catchment scale in
104 training young and senior researchers and their potential for regional scientific
105 advancement.

106

107 **2. MOTIVATIONS TO SET UP THE EXPERIMENTAL CATCHMENT** 108 **MONITORING**

109 In the early 2000s, the Government of Rio Grande do Sul (RS; the southernmost state of
110 Brazil) created a project to improve land management as a key component of its
111 program against rural poverty. The Rural Poverty Program, known as RS-Rural, aimed
112 to implement public policies to improve the conditions of natural resources (soil, water,
113 and vegetation) under degradation, local infrastructure (water supply, rural sanitation,
114 and unpaved road improvement), and productive infrastructure (family agribusiness

115 support) in poverty-stricken rural areas. The project aimed to enhance the rural
116 communities' quality of life by increasing economic activities and improving natural
117 resource management.

118

119 In RS, rural poverty areas are mainly located in regions with soils of low agricultural
120 aptitude characterized by high slopes and stoniness, shallow depths, limited soil
121 fertility, and low water retention capacity. Under these conditions, intensive cultivation
122 leads to soil and water quality degradation in response to water erosion. Hence, the soil
123 has reduced productive capacity, limited income generation, and intensified rural
124 poverty. In the early of 2000s in RS, there were roughly 234,000 small farmers below
125 the poverty threshold (income below 1.5 minimum wage; \$USD 300.00/month per
126 family) (World Bank, 2005). To alleviate rural poverty, public investments must be
127 initially directed to decreasing natural resource degradation by implementing soil and
128 water conservation practices, thereby increasing land productivity. Based on these
129 conditions, the RS government, in partnership with the World Bank, founded the
130 Natural Resources Management and Rural Poverty Alleviation Project-CPL 41480
131 (World Bank, 2005).

132

133 In order to evaluate the impacts of this promising project, the World Bank
134 commissioned a study from the local government to quantify the socioeconomic
135 impacts on natural resources. The method chosen to assess the effects on natural
136 resources was based on installing four hydrological and soil quality monitoring units in
137 different areas; these four monitoring units were chosen by EMATER-ASCAR, the
138 UFSM (Federal University of Santa Maria) Department of Soil Science, and the
139 UFRGS (Federal University of Rio Grande do Sul) Hydraulic Research Institute to
140 represent areas with different geologies and soil characteristics. As a geographic unit,
141 the researchers and extensionists selected ~1-km² catchments with first- to second-order
142 drainage networks. Soil and water quality monitoring was then established to provide
143 indicators of the impacts of the project's actions, and suspended sediment concentration
144 and sediment yield were selected among the water quality indicators as they deliver
145 sensitive indicators of the effectiveness of the project's soil and water conservation
146 measures.

147

148 The method used to assess sediment yield consisted of evaluating the rainfall,
149 streamflow, and suspended sediment concentration during rainfall events using a high
150 frequency data monitoring and long-term analysis. The soil conservation actions
151 conducted by the farmers were evaluated at different moments of the project as the
152 initial phase (without project intervention from 2001 to 2003), the intermediate phase
153 (when actions were ongoing from 2003 to 2004), and their final phase (when all
154 scheduled actions were undertaken after 2004). At the time of the installation of the
155 monitoring catchments selected for the project, the farmers had not yet implemented
156 soil and water conservation practices. On the contrary, the international scenario of
157 rising tobacco prices, which was also a result of the collapse of the African production
158 system, has led to an increase in the cultivated area, including in the Arvorezinha
159 catchment. Results on soil quality for the four studied catchments are presented in
160 Reichert et al. (2022). One of the strategic pillars of this project was to reduce erosion
161 and sediment inputs to watercourses. The goal was to promote the sustainable use of
162 soils and water and improve local infrastructure in order to evaluate the efficiency of
163 this program and promote a broader and longer-term application (Merten & Minella,
164 2006; Minella, 2007).

165
166 The long-term monitoring in the Arvorezinha experimental catchment was an outdoor
167 laboratory integrating different fields of knowledge, mainly hydrology and soil science.
168 In addition, studies have also contributed to the training of professionals at different
169 academic levels (technical, undergraduate, and graduate). More notably, the monitoring
170 work carried out in the Arvorezinha catchment has created numerous opportunities for
171 cooperation among international researchers, leading to significant scientific
172 contributions to test and improve monitoring procedures and methods. Without this
173 international cooperation, it would not have been possible to advance knowledge in all
174 these research fields, especially those related to the dynamics of sediments between the
175 catchment hillslopes and the river channel. Understanding these dynamics was only
176 possible using techniques such as the sediment fingerprinting method and caesium-137
177 inventories combined with traditional hydrological monitoring techniques (Minella et
178 al., 2008a; 2014; Tiecher et al., 2017b).

179
180 The use of monitoring and modeling techniques in the Arvorezinha catchment was
181 initiated by Professor Desmond E. Walling of the Department of Geography of the

182 University of Exeter (United Kingdom). Professor Desmond E. Walling visited Brazil
183 on two occasions to promote scientific meetings within the scope of the International
184 Commission of Continental Erosion (ICCE) of the International Association of
185 Hydrological Science (IAHS). On his first visit, together with Professor Pierre M.
186 Bordas of the Hydraulic Research Institute of the University of Rio Grande do Sul, they
187 organized a meeting called “The Symposium on Sediment Budgets” in 1988 in Porto
188 Alegre (Bordas & Walling, 1988). Professor Walling’s second visit to Brazil took place
189 in 2005 in Foz do Iguaçu, where he organized, in collaboration with USGS scientist
190 Arthur J. Horowitz, the IAHS-ICCE symposium called “Sediment Budget” (Walling &
191 Horowitz, 2005). The studies carried out by Professor Desmond E. Walling generated
192 considerable interest among the Brazilian scientific community. This influence
193 culminated with the involvement of Professor Desmond E. Walling in the monitoring
194 work carried out in the Arvorezinha catchment. Following this experience, the concepts
195 and methods applied in Arvorezinha have inspired other research groups working with
196 erosion studies at the catchment scale in Brazil.

197

198 **3. THE STUDY CATCHMENT**

199

200 The Arvorezinha catchment is located on the edge of the Brazilian meridional plateau
201 (28°52'S and 52°05'W) in southern Brazil (Figure 1). The catchment has an area of 1.23
202 km² and drains towards the Taquari River, one of the main tributaries of the Guaíba
203 lake, which supplies water to over four million inhabitants of the Porto Alegre
204 metropolitan area (roughly 37.7% of the inhabitants in the state) (IBGE, 2018). The
205 Arvorezinha catchment altitude varies between 560 and 720 m. The topography is
206 gently rolling in the upper third of the catchment with average slope gradients of ca.
207 7%. However, in its lower parts, the topography is characterized by shorter and steeper
208 slopes (ca. 84%). The area is predominantly underlain by volcanic rocks, which weather
209 to produce fertile Entisols and Inceptisols. The climate is mesothermal super-humid
210 subtropical (i.e., Cfb), and the average annual rainfall is 1938 mm evenly distributed
211 throughout the year. The catchment’s physiographic characteristics were important for
212 describing the processes of interest. The proximity of the crop fields to the drainage
213 network and the narrow width of the riparian forest, for instance, determines the high
214 connectivity between hillslope processes and the river channel. These characteristics

215 made it possible to shed more light on the cause-and-effect relationships between the
216 erosion processes at hillslopes and sediment yield at the river channel.

217

218 The experimental Arvorezinha catchment involves approximately 16 rural properties
219 with surface areas ranging from 5 to 20 ha. This catchment scale was chosen for
220 monitoring based on EMATER-ASCAR's ability to implement soil conservation
221 practices within a few years. Land use is agricultural, and most fields are cultivated with
222 tobacco and soybean, the latter of which sharply increased after 2012. Soil erosion
223 (inter-rill and rill erosion) is the primary soil degradation process generating large
224 amounts of sediment transferred to watercourses, and small gullies are found in the road
225 ditches and fields where road runoff is discharged.

226

227 The monitoring of the Arvorezinha experimental catchment documented changes in
228 sediment yield in response to improved land management involving minimum-till
229 cultivation, a denser soil cover maintenance using cover crops, and crop rotation.
230 Hydrological monitoring started in 2001 with the systematization of the measurement of
231 precipitation (P), streamflow (Q), and suspended sediment concentration (SSC) in a
232 section composed of a Parshall flume (6 feet) and a walkway for sediment sampling.
233 Monitoring has been the main activity since then, from which all other studies were
234 derived with the goal of better understanding the hydrological and erosion behavior.
235 The monitoring structure comprises water depth sensors, turbidimeters, rain gauges,
236 meteorological stations, and sediment samplers. The measurement strategy is based on
237 on-site monitoring of significant rainfall-runoff events to collect samples for SSC
238 analysis and check the validity of level sensors. In addition, local farmers were trained
239 and participated in the monitoring by recording the daily rainfall values at rain gauges
240 distributed across the catchment as well as by taking care of the monitoring
241 infrastructure.

242

243 [Insert Figure 1]

244

245 **4. THE PROCESSES OF INTEREST**

246 **4.1 Hydrological monitoring**

247 The catchment was considered to provide the fundamental unit under investigation and
248 relied on "sediment yield" as the main variable of interest. The studies have sought to

249 improve monitoring techniques and hydrological modeling to enhance the design of soil
250 and water conservation projects at the catchment scale. Monitoring required special
251 attention to rainfall-runoff events. During rainfall events, the streamflow responses
252 occur within minutes or a few hours, triggering soil detachment and sediment transport
253 to the catchment outlet. Thus, the strategy of monitoring P, Q, and SSC needed to be
254 efficient in the follow-up of significant events. The 10-minute interval was defined as
255 the optimum data acquisition interval to describe the variables P, Q, and SSC and
256 optimize data collection and organization, which proved to be enough to represent the
257 variations and correctly describe the processes.

258

259 Whenever possible, significant events were monitored on-site, with sampling being
260 conducted using US DH-48 suspended sediment samplers associated with turbidity (T)
261 measurements to improve SSC temporal discretization. Numerous studies have been
262 carried out to evaluate the efficiency of the turbidimeter in estimating SSC and to define
263 protocols for its installation, calibration, and use as a complementary measurement to
264 direct SSC monitoring (Minella et al., 2008b; Merten et al., 2014ab; Dalbianco et al.,
265 2017). Prioritizing SSC data collection during events was pivotal to accurately
266 estimating sediment yield (SY). In addition to suspended sediment monitoring, bedload
267 discharge (2004–2007) was also monitored (BL-84 sampler) to quantify the importance
268 of this component to the total SY in the catchment. The results demonstrated that the
269 bedload flux ranged from 0.24 to 44 g m⁻¹ s⁻¹. The contribution of bedload to the total
270 sediment yield varied between <1% and 60%, depending on peak flow (Merten &
271 Minella, 2014).

272

273 Collecting data of the events allowed researchers to analyze the effects of variations in
274 land use and soil management as well as impacts related to climate on annual sediment
275 yields, allowing the hydrological and erosive behavior of the catchment to be more
276 accurately described. Interpreting medium and large magnitude hydrographs, which are
277 responsible for the greatest soil losses, was fundamental to understanding runoff
278 formation and propagation and sediment mobilization and transfer (sedigraphs). Four
279 events are presented in Figure 2 to exemplify the response pattern of Q and SSC to
280 rainfall events. To estimate SY throughout the monitoring period, a multiple linear
281 regression analysis was used to quantify the relative contributions of different variables
282 (climate, land use, and soil management). The long-term monitoring allowed us to

283 interpret the combined effects of climate and anthropogenic activities on SY over the
284 years (Figure 3) (Minella et al., 2009a; 2018).

285

286 [Insert Figure 2]

287

288 [Insert Figure 3]

289

290

291 Data collection has been used to describe surface runoff formation and propagation and
292 the associated processes. Among them, we can highlight: a) the existing hysteresis
293 between Q and SSC during events that help describe sediment transport behavior in
294 catchments (Minella et al., 2011; Barros et al., 2014a); b) determining the bedload
295 discharge rating curves (Merten & Minella, 2014); c) quantifying chemical substance
296 transfers to the drainage network (Merten & Minella, 2002; Bender et al., 2018; Barros
297 et al., 2020; Bastos et al., 2021); d) analyzing the effects of climate and conservation
298 practices on the behavior of hydrological variables with a view to conservation planning
299 (Ramon et al., 2017; Menezes et al., 2020) and evaluating the mathematical models'
300 efficiency (Uzeika et al., 2012; Barros et al., 2021a; Silva et al., 2021).

301

302 **4.2 Modeling runoff and sediment yield**

303 Mathematical models for predicting sediment yield are valuable tools for solving
304 numerous issues, such as understanding and controlling erosion on catchment hillslopes
305 (de Vente et al., 2013; Rodriguez-Lloveras et al., 2015; Nadal-Romero et al., 2018),
306 controlling erosion to reduce river channel and reservoir siltation (Walling & Fang,
307 2003; Stolte et al., 2003; Mutua et al., 2006), and preventing the pollution of water
308 resources.

309

310 In the Arvorezinha catchment, the mathematical modeling of SY became feasible
311 because a large hydrological database was constructed and the compilation of
312 information obtained in the field regarding changes in land use and soil management. In
313 this way, the first five years (2002–2007) of monitoring were oriented toward obtaining
314 consistent hydrological data. In the following phase (2008–2013), the mathematical
315 models were used to better define the spatial representation of the factors related to the
316 rainfall-runoff transformation and erosive and depositional processes associated with

317 these events. Hence, great efforts were made to represent the physical environment,
318 enabling physically-based models to be applied; the hydrological data gathering was
319 also incremented, as previously described.

320

321 The basic information of the physical environment was derived from the relief, soil
322 type, and surface conditions (land use and soil management); the mapping of this
323 information was gradual and guided by field observations. Walking around the
324 catchment and exchanging information with the farmers and rural extension personnel,
325 especially after precipitation-runoff events, helped shed more light on the hydrological
326 response as a function of geomorphological features and surface conditions. Interacting
327 with the catchment inhabitants was essential for the researchers to understand the
328 farmers' perception of soil degradation and their acceptance and capacity to implement
329 soil and water conservation practices.

330

331 The characterization of the physical environment started with mapping the relief,
332 drainage and road network, land use, soil type, and physical and hydrological soil
333 properties. The greatest effort was dedicated to describing the spatial variability of the
334 soil's hydrological properties (e.g., saturated hydraulic conductivity) and the
335 representation of the topography. The primary surveys and information obtained are
336 described in theses and dissertations developed in the catchment (Minella, 2003, 2007;
337 Moro, 2011; Dalbianco, 2009, 2013; Barros, 2012, 2016; Schlesner, 2017; Bernardi,
338 2018).

339

340 Mathematical modeling was used to represent the effects of land use and soil
341 management on reducing SY at the catchment scale and to represent spatial-temporal
342 erosional and sedimentation processes on catchment hillslopes. The Limburg Soil
343 Erosion Model (LISEM) has been the most widely used model in the Arvorezinha
344 catchment scale (Hessel & Jetten, 2007; Jetten, 2018). The equations explicitly express
345 the effects of soil conservation practices on important processes such as infiltration,
346 rainfall-runoff transformation, and erosion. The model is spatially distributed, which
347 allows the parameter values of the equations to be measured in detail in the spatial
348 complexity of the catchment. Lastly, the model simulates specific rainfall-runoff events
349 at sub-hourly intervals, enabling a detailed representation of the hydrograph and
350 sedigraph.

351

352 The strategies used to improve the modeling ability were based on different methods,
353 including a) exploring the set of monitored events to represent hydrological processes
354 under different conditions of climate and land use and soil management (Barros et al.,
355 2014b; Menezes et al., 2020); b) detailed spatial characterization of the soil parameters
356 used by the model (Barros et al., 2014a, 2021b); c) representation of the effects of
357 unpaved roads on runoff propagation and erosion occurrence (Silva et al., 2021); d)
358 improving the separation procedures of the different runoff types (superficial and
359 subsurface) (Bernardi, 2018; Barros et al., 2021a); e) testing different equations that
360 represent the soil detachment by runoff (Schlesner, 2017); f) identifying the main
361 sediments sources in the catchment in order to support the model results in spatial terms
362 (Minella et al., 2014). The locations where soil characterization was carried out to
363 parameterize the LISEM equations are illustrated in Figure 4, and a sample of the
364 results in the outlet and catchment hillslope achieved using the model is provided in
365 Figure 5.

366

[Insert Figure 4]

368

[Insert Figure 5]

370

371

372 Another important contribution to understanding hydrological processes in the
373 catchment was the participation of the Arvorezinha experimental catchment in the Soils
374 Under Global Change (SOGLO), a project developed by a consortium of European
375 universities (BELSPO, 2016). Among the numerous research activities developed in
376 this project, those that described the composition and spatial pattern of the streamflows
377 (surface and subsurface) were crucial for better understanding the rainfall-runoff
378 processes in the Arvorezinha catchment. For example, Robinet et al. (2018) evaluated
379 the degree of intervention of human action through changes in water pathways (surface
380 and subsurface).

381

382 **4.3 Linking catchment hillslope erosion processes into the drainage network**

383 Monitoring Q and SSC makes it possible to calibrate the LISEM. In this case, the model
384 performance was evaluated considering the data observed at the catchment outlet.

385 However, model efficiency must also consider information about the spatial variability
386 of SY and the outlet results. This is important because error compensation within the
387 catchment can generate an acceptable result at the outlet. This characteristic of open
388 systems is known in modeling as equifinality (Beven, 2006; Her & Chaubey, 2015), in
389 which different model configurations (e.g., different parameter values) can generate
390 similar or equally acceptable simulations. Hence, it is fundamental for monitoring
391 strategies to be capable of verifying the behavior of sediment mobilization and transfer
392 within the catchment. In this sense, identifying sediment sources has been crucial to
393 complement the results of traditional monitoring with those generated by physical and
394 distributed modeling.

395

396 Identifying sediment sources is a technique applied to eroded sediments that provides a
397 useful complement to the information generated by traditional monitoring techniques
398 (Du & Walling, 2017; Walling, 2013). The results of sediment source identification can
399 contribute to verifying if the spatial and temporal patterns of sediment yield modeling in
400 the catchment are correct. This is especially important when different erosional
401 mechanisms (inter-rill, rill, and channel erosion) are observed in the catchment and
402 when connectivity affects the transfer of eroded sediments from catchment hillslopes to
403 the drainage network and catchment outlet (de Vente et al., 2007; Walling, 1983).

404

405 The information about the sediment source further enhances the importance of
406 monitoring because it expands the result of SY, indicating the proportions of each
407 source to the sediment reaching the catchment outlet. In addition, it enhances the
408 improvement of the models because it allows the efficiency of the models to be
409 evaluated by spatially representing the processes and/or the types of processes operating
410 within the catchment. Mathematical models can represent erosive processes (soil
411 detachment, sediment transport, and deposition) with an increasing level of spatial and
412 temporal discretization (Jetten et al., 1999; Baartman et al., 2012). Nevertheless, the
413 validation of the simulation results regarding erosive processes and SY from catchments
414 necessarily depends on spatially distributed data about where and when erosion and
415 sediment transfer occurs in the catchment.

416

417 Hydrological monitoring combined with sediment tracing techniques demonstrates the
418 individual variations of the source contributions, even if the absolute value of SY does

419 not change significantly. Minella et al. (2008a) evaluated the change in SY in periods
420 “without” and “with” soil conservation practices by combining sediment source
421 identification with traditional monitoring. After the introduction of conservation
422 practices (minimum till associated with cover crops), SY sharply decreased in croplands
423 and unpaved roads and the contribution of channel erosion increased. The study showed
424 that introducing conservation practices changed the emission pattern of the sources
425 between field crops, unpaved roads, and stream channels due to the change in surface
426 runoff behavior and transport capacity.

427

428 Cesium-137 measurements have been combined with SY measurements and
429 fingerprinting of the source of the fine sediment output to establish a provisional
430 sediment budget for the entire catchment. Cesium-137 measurements were used to
431 estimate medium-term erosion and deposition rates along transects across the cultivated
432 slopes and to quantify sedimentation rates within valley floor sediment sinks. These
433 data have been used to estimate sediment redistribution rates within the cultivated areas
434 and sediment accumulation in the valley floor sinks. The information provided by the
435 three primary data sources has been integrated to establish the sediment budget for the
436 catchment over the past 57 years.

437

438 As illustrated in Figure 6, traditional monitoring integrated with the sediment tracing
439 technique improved the spatial and temporal interpretation of the catchment’s erosive
440 processes (rill and interrill erosion). It contributed to verifying the consistency between
441 the changes in soil management and those in the respective source contributions.
442 Notably, the analyses of each source’s SY are based on the absolute contribution ($t.km^{-2}$)
443 derived by multiplying the relative contribution of each source and the monitored SY
444 in each event.

445

446 [Insert Figure 6]

447

448

449 In addition to the influence of land use and soil management, SY is strongly controlled
450 by the magnitude of rainfall-runoff events. Obtaining information during different
451 events throughout the year (inter-event pattern) captures the seasonal variability of land
452 use and soil management. The inter-event pattern is also an alternative for verifying the

453 pattern of source contributions. During rainfall-runoff events of different magnitudes,
454 some sediment sources are activated while others are not. An example frequently
455 reported in the literature is the increased relative contribution of sediment from unpaved
456 roads during lower magnitude events and from catchment hillslopes during higher
457 magnitude events (Minella et al., 2009b; Collins et al., 2010; Tiecher et al., 2017a).

458

459 An important challenge in catchment research is defining the number of samples
460 necessary to correctly represent the processes of interest. In the case of the sediment
461 “fingerprinting” approach, a mathematical-statistical model was developed to determine
462 the number of samples required for better characterization and reducing uncertainties
463 related to the source (Clarke, 2015; Clarke & Minella, 2016). Defining the number of
464 samples that minimizes sampling and analysis costs while maximizing their
465 discrimination and classification ability is key to improving monitoring and modeling
466 efficiency. In this case, statistical analysis allows one to quantify the increased
467 uncertainty by reducing the number of samples (of both sources and suspended
468 sediments) according to the number of sources involved and their variability.

469

470 **5. HISTORY OF SEDIMENT FINGERPRINTING STUDIES IN THE** 471 **ARVOREZINHA CATCHMENT: ADVANCES AND INFLUENCES ON OTHER** 472 **CATCHMENTS**

473 Sediment tracing in Brazil began at the Arvorezinha catchment, where the first master
474 thesis (Minella, 2003) and the first doctoral dissertation (Minella, 2007) were
475 performed, adapting the sediment fingerprinting method to the Brazilian conditions.
476 Subsequently, the contribution of sediment sources in the Arvorezinha catchment was
477 also the main topic of two additional doctoral dissertations (Maier, 2013; Tiecher,
478 2015). From these studies, 12 scientific articles have been published so far (Minella et
479 al., 2004, 2007, 2008a, 2009b, 2014; Clarke, 2015; Clarke and Minella, 2016; Tiecher et
480 al., 2015, 2016, 2017, 2019, 2021), which will be briefly discussed below whilst
481 focusing on the respective advances provided by these articles regarding studies
482 conducted in other catchments in Brazil.

483

484 “Start small”— this makes a lot of sense when evaluating the evolution of sediment
485 tracing studies not only in Brazil but in the Arvorezinha catchment itself. The evolution
486 of sediment fingerprinting research that started in the Arvorezinha catchment occurred

487 following three main topics of investigation: (i) methodological advances, (ii) providing
488 multiple lines of evidence regarding sediment dynamics, and (iii) expanding research
489 across Brazil and increasing catchment scale and complexity.

490

491 **5.1 Methodological advances**

492 The Arvorezinha catchment has a relatively long history of monitoring. It is associated
493 with a range of highly detailed information on soil type, land use, topography, and
494 climate, among others, which was unprecedented in Brazil. In addition, the catchment
495 has a long history of sediment fingerprinting studies using conventional tracers
496 (geochemistry) based on analyzing chemical element concentrations analyzed in a
497 highly detailed sampling grid of potential sources of sediment (in the order of >30
498 samples km²) (Minella et al., 2008a, 2014). The spatial representation of unpaved roads
499 and drainage channels as sediment sources were also important challenges in applying
500 the technique in the Arvorezinha catchment. The sampling scheme for unpaved roads
501 and stream channels as sediment sources followed a protocol developed for the
502 catchment characteristics. The first strategy was to map the different soils that made up
503 the roads and streams network. Subsequently, the sites with active erosion were
504 identified in each soil unit of each source. The samples were composed of 20 sub-
505 samples collected in homogenous stretches of approximately 20 m (Minella et al.
506 2008a).

507

508 This made it possible to use the Arvorezinha catchment as a model to test and validate
509 new tracing techniques, something that would be practically impossible to implement in
510 a large catchment and/or with a shorter monitoring period. Various tracing strategies
511 were tested in the catchment, including geochemistry and mineralogy (Minella et al.
512 2008a), radionuclides (Minella et al., 2014), and alternative methods such as those
513 relying on near-infrared spectroscopy (Tiecher et al., 2016), mid-infrared spectroscopy
514 (Tiecher et al., 2017b), visible ultra-violet spectroscopy (Tiecher et al., 2015), color
515 properties (Tiecher et al., 2015), phosphorous (P) fractions obtained from sequential
516 chemical fractionation (Tiecher et al., 2019), and different spectral pre-processing
517 techniques and chemometric models based on reflectance spectroscopy (Tiecher et al.,
518 2021).

519

520 Subsequently, some of these techniques, which were initially tested and validated in the
521 Arvorezinha catchment, were also applied in other river catchments in southern Brazil,
522 for example, Ramon et al. (2020), Valente et al. (2020), and Dambroz et al. (2022). The
523 first two studies (Ramon et al., 2020; Valente et al., 2020) provided original approaches;
524 they compared the results of spectroscopic tracers with those obtained with
525 conventional methods (e.g., elemental concentrations, radionuclides). Valente et al.
526 (2020) used color properties and visible ultraviolet spectroscopy in two small-paired
527 catchments (one with commercial eucalyptus plantations [0.83 km²] and the other with
528 grassland used for livestock farming [1.10 km²]) in the Brazilian Pampa biome. Ramon
529 et al. (2020) used spectroscopy and color parameters in a much larger catchment
530 (Conceição River [804 km²]), with predominantly deep and strongly weathered Oxisols
531 under no-till. In addition, the authors also successfully introduced magnetic properties
532 to improve sediment source discrimination. More recently, Dambroz et al. (2022) in
533 southern Brazil and Amorim et al. (2021) in a semi-arid region of northeastern Brazil
534 used spectroscopy alone to investigate the contribution of sediment sources in the
535 Guarda Mor (18.5 km²) and Goiana (2857 km²) catchments, respectively. Therefore, the
536 lessons and tests carried out with alternative tracers in the Arvorezinha catchment were
537 fundamental to validating the use of these reflectance spectroscopy techniques as a
538 reliable, fast, and low-cost method without generating chemical residues to be used for
539 quantifying the contribution of sediment sources in catchments across Brazil.

540

541 Together with the research of alternative spectroscopy-based tracers, other studies were
542 developed in Brazil testing the use of mineralogical attributes and tracers based on
543 pedological knowledge instead of purely applying statistical methods (Miguel et al.,
544 2014; Batista et al., 2019). Both studies demonstrated that the composition of the
545 mineral fraction of the soil holds valuable information to be used in fingerprinting
546 studies, further supporting the use of diffuse reflectance as these techniques were highly
547 sensitive to the mineralogical and chemical composition of soils and sediments (Tiecher
548 et al., 2015, 2016, 2021).

549

550 **5.2 Providing multiple lines of evidence regarding sediment dynamics**

551 The vast dissemination of sediment fingerprinting studies in recent years around the
552 world is outstanding (Collins et al., 2020). Nevertheless, most of these studies are
553 generally based on the sediment fingerprinting method, providing a unique line of

554 evidence to better understand the dynamics of sediment supply in each catchment. Few
555 researchers have focused on complementing sediment fingerprinting with catchment
556 monitoring techniques and how multiple lines of evidence can help shed more light on
557 sediment transport dynamics. Lessons from pioneering work in this combined approach
558 are valuable even though it has not yet been widely adopted in sediment fingerprinting
559 studies conducted across Brazil. Minella et al. (2008a) demonstrated the potential value
560 of combining sediment source tracing techniques with traditional monitoring
561 approaches when documenting the impact of improved land management on catchment
562 SY. Minella et al. (2014) used ^{137}Cs inventory measurements combined with SY
563 measurements and sediment fingerprinting data to establish a provisional sediment
564 budget for the Arvorezinha Catchment.

565

566 In the same line of research, Dambroz et al. (2022) used topographic attributes acquired
567 from a digital elevation map and a spatially distributed erosion model (WaterSed) to
568 simulate runoff, erosion, sediment yield, and sediment source contributions estimated
569 using sediment fingerprinting based on near-infrared spectroscopy. The authors reported
570 that combining different environmental diagnosis techniques effectively outlined the
571 fragility of those areas where overland flow may accumulate and lead to accelerated soil
572 degradation processes. Moreover, Tiecher et al. (2022) have also demonstrated that
573 using sediment source tracing techniques, combined with sediment flux monitoring, can
574 improve our understanding of the sediment source contributions to one of the largest
575 lakes in South America: the Guaíba Lake (482 km²). They used publicly available data
576 from long-term monitoring of river discharge and SSC (1978–2019) combined with the
577 shorter-term monitoring of chemical element concentrations in bed sediment (2000–
578 2011) as geochemical tracers. The estimates of the sediment contributions from the four
579 main tributaries (Jacuí, Caí, Sinos, and Gravataí rivers) were found to be similar for
580 both approaches. These findings demonstrated that the sediment fingerprinting approach
581 combined with sediment flux monitoring could provide a valuable means of estimating
582 the respective sediment contributions from individual tributaries in large and complex
583 delta systems and may provide a powerful tool to guide water resource management.

584

585 **5.3 Expanding research across Brazil and increasing catchment scale and**
586 **complexity**

587 The first sediment fingerprinting study in South America was carried out in the
588 Arvorezinha catchment, more precisely, in a sub-catchment with an area of only 0.57
589 km² (Minella et al., 2003). Since then, most studies on the contribution of sediment
590 sources have focused on small catchments with surface areas <10 km², all located in Rio
591 Grande do Sul State (Table 1). Gradually, the catchments' sizes have increased, and
592 studies have spread to other Brazilian states (Minas Gerais, Pernambuco, and Distrito
593 Federal). After 2014, some studies were also developed at an intermediate scale
594 (catchment areas ranging from 10¹ to 10² km²) (Miguel et al., 2014; Batista et al., 2019;
595 Dambroz et al., 2022). In addition, between 2014 and 2020, sediment fingerprinting
596 studies were carried out in catchments with a total area of between 800 and 1200 km²
597 (Franz et al., 2014; Tiecher et al., 2018; Batista et al., 2019; Ramon et al., 2020).
598 Nevertheless, research has only been carried out in catchments larger than 2000 km²
599 since 2017 (le Gall et al., 2017; Tiecher et al., 2017c; Amorim et al., 2021). More
600 recently, the target catchment area jumped to 5942 km² in a catchment experiencing a
601 widespread land-use change in the last years (Ramon et al., 2020), where the conversion
602 of natural grasslands into cropland accelerated soil erosion and sediment delivery to the
603 river systems. In addition, two more tentative approaches have used the sediment
604 collected in the tributary outlet as potential sources to estimate the contribution of
605 sediment from these tributary catchments to that supplied to a larger drainage system,
606 such as the Uruguay River (266,132 km²) (Ramon, 2021) and the Guaíba Lake (85,139
607 km²) (Tiecher et al., 2022).

608

609 The sediment source research in the Arvorezinha catchment allowed studies to be
610 applied to larger catchment sizes at different locations across Brazil and zones
611 characterized by source types of increasing complexity. Studies that initially focused on
612 two to three potential sources and mainly focused on land uses have turned into studies
613 with four to five potential sources with different sediment sampling strategies (Tiecher
614 et al., 2018), contrasted particle sizes (Rodrigues et al., 2018; Amorim et al., 2021),
615 different mathematical models (Batista et al., 2019), stable isotope and radionuclide
616 tracers (le Gall et al., 2017; Valente et al., 2020; Ramon, 2021), potential sources of
617 sediment based on the soil type (le Gall et al., 2017), catchment sub-region (Batista et
618 al., 2019), and tributaries (Tiecher et al., 2022). Despite the advances, the lack of
619 research in urban (Franz et al., 2014; Poleto et al., 2009), forest (Rodrigues et al., 2018;
620 Valente et al., 2020), and natural grassland catchments is still notable (Ramon, 2021).

621 Moreover, regions characterized by the widespread expansion of agricultural areas, such
622 as the Cerrado and Amazon Rainforest biomes, remain unexplored by sediment
623 fingerprinting studies. Nonetheless, research has consistently shown that despite the
624 increase in the area cultivated under no-till, croplands remain the primary source of
625 sediment in rural catchments in Brazil, demonstrating that the soil conservation
626 measures and practices implemented so far remain insufficient to reduce the transfer of
627 sediments to water bodies, together with the pollutants adsorbed therein (Tiecher et al.,
628 2017a; Bender et al., 2018; Barros et al., 2020). Furthermore, studies demonstrate that
629 unpaved roads supply a potentially significant source of sediment, despite occupying a
630 minor fraction of catchment surface areas, and that their construction must be better
631 planned in the landscape (Minella et al., 2008a; Poletto et al., 2009; Tiecher et al.,
632 2017b; Rodrigues et al., 2018; Valente et al., 2020; Amorim et al., 2021; Silva et al.,
633 2021; Ebling, 2022).

634

635

[Insert Table 1]

636

637 **6. CATCHMENT STUDIES AND THEIR RELEVANCE FOR SCIENTIFIC** 638 **PRODUCTION AND PROFESSIONAL TRAINING**

639 The long-term monitoring activities developed in the Arvorezinha catchment resulted in
640 significant academic and scientific production, demonstrating the socioeconomic
641 feasibility of these projects. The number of articles, dissertations, and theses published
642 in triennial periods using data obtained in the Arvorezinha experimental catchment is
643 shown in Figure 7. The Arvorezinha experimental catchment has proven to be an
644 effective tool for academic training and promoting scientific interactions and
645 collaborations. Besides the academic and scientific production, it is important to
646 emphasize that the project's actions also improved the quality of life of the families
647 residing in the catchment, considering the impacts of best soil management practices,
648 rural sanitation, and water quality improvements.

649

650

[Insert Figure 7]

651

652 In the project's early years (2001-2006), there were intense field activities. Besides the
653 monitoring, field surveys were needed to characterize the soils, relief, land use, and soil
654 management, which were essential for mathematical modeling. Despite the great efforts

655 made to consolidate the monitoring structure, scientific production was low during this
656 period.

657

658 The next three-year period (2007–2009) resulted in a cumulative curve of the research
659 products due to the accumulation of information necessary to describe the hydrological
660 processes occurring at the catchment scale. During this period and the following one
661 (2010–2012), the main works involved the sediment fingerprinting method and its
662 contribution to improving our understanding of erosion processes in the catchment. The
663 descriptive and exploratory analyses of the first studies (2001–2009) made it possible to
664 integrate multiple factors of the erosion process. In these terms, the “sediment
665 fingerprinting approach” was essential to provide observational robustness to use
666 mathematical modeling and shed more light on the multiple integrated hydrological
667 processes.

668

669 From 2010 onwards, it is possible to observe a change in scientific and academic
670 production (Figure 8). In this period, the sediment fingerprinting studies targeted wider
671 objectives, seeking to improve tracing methods, highlighting the use of variables
672 derived from spectroscopy, and analyzing uncertainties associated with the number of
673 samples collected in the field. The scientific results obtained and the on-site
674 demonstrations of the techniques developed by other research groups stimulated the
675 development of similar projects in other experimental rural catchments across Brazil.

676

677

[Insert Figure 8]

678

679 After ten years of monitoring, combining information derived from different studies,
680 which involved the quantification of Q, SSC, and SY and sediment fingerprinting
681 contributed to using physically-based modeling and constructing a broad and, at the
682 same time, detailed panorama of soil erosion processes in the catchment. The studies
683 demonstrate the plurality of approaches by integrating multiple research groups with
684 different backgrounds.

685

686 **7. CONCLUDING REMARKS**

687 A vast array of people conquered the interdisciplinarity of research conducted in the
688 Arvorezinha catchment. Scientists, farmers, and rural extension staff, motivated by the

689 interest in implementing the results obtained during the monitoring period, contributed
690 to this project's success. By observing the advances that the Arvorezinha experimental
691 catchment has provided to the community, we can emphasize the following points:
692 1 - Public investments in education and research generate incalculable returns in
693 professional training and useful results for socioeconomic and environmental
694 development.
695 2 - The importance of installing and maintaining experimental catchments for basic
696 training in hydrology, development of modern environmental monitoring techniques,
697 and improvement of mathematical modeling.
698 3 - The importance of using complementary techniques, such as the "sediment
699 fingerprinting approach," along with traditional hydrological monitoring and
700 mathematical modeling methods to better understand the link between hydrological and
701 erosion processes in response to catchment land use and soil management changes.
702 4 - The importance of a long-term hydrologic monitoring period (frequently more than
703 10 years) to better evaluate the impacts of soil and water conservation projects
704 considering that the adoption of conservationist practices by farmers is a gradual
705 process and subject to setbacks, as in the Arvorezinha catchment.
706 5- The relevance of national and international scientific collaboration between national
707 and international reference groups.

708

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732

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1088 **TABLE**

1089 Table 1. Sediment sources investigated and catchment name, size, and location where sediment fingerprinting studies were conducted in Brazil.

Catchment/River	State	Area (km ²)	Sediment sources	Reference
Arvorezinha	RS	1.2	Cropland, Stream channel, Unpaved roads	Minella et al. (2003; 2008; 2009; 2014); Minella and Merten (2011); Clarke and Minella (2016); Tiecher et al. (2015; 2016; 2017b; 2019; 2021)
Agudo	RS	4.80	Cropland, Stream channel, Unpaved roads	Minella et al. (2007)
Dilúvio	RS	0.83	Paved road, Unpaved road, Stream channel	Poleto et al., (2009)
Júlio de Castilhos	RS	0.80–1.43	Cropland, Stream channel, Unpaved roads, Grasslands	Tiecher et al. (2014; 2017a)
Eldorado do Sul	RS	0.98	Eucalyptus, Stream channel, Unpaved roads	Rodrigues et al. (2014, 2018)
São Gabriel	RS	0.83–1.10	Eucalyptus, Stream channel, Unpaved roads, Pasture	Valente et al. (2020)
XV de Novembro	RS	0.67-1.14	Crop fields, Unpaved roads, Stream channel	Ebling (2022)
Posses	MG	12	Cropland, Grassland, Unpaved roads, Subsoil	Batista et al. (2019)
Guarda-Mor	RS	18.5	Forest, Stream channel, Topsoil, Unpaved roads	Dambroz et al. (2022)
Vacacaí-Mirim	RS	20	Topsoil, Stream channel, Unpaved roads	Miguel et al. (2014)
Conceição	RS	804	Cropland, Stream channel, Unpaved roads, Grassland, Gully	Tiecher et al. (2018); Ramon et al. (2020)
Paranoá lake	DF	1,046	Cropland, Urban area, Semi-natural	Franz et al. (2014)
Ingaí	MG	1,200	Upper catchment, Middle catchment, Lower catchment	Batista et al. (2019)
Guaporé	RS	2,032	Cropland, Stream channel, Unpaved roads Ferralsols, Nitisols, Acrisols, Leptosols, Luvisols	Tiecher et al. (2017c) le Gall et al. (2017)
Goiania	PE	2,857	Sugarcane, Unpaved roads, Cropland, Channel banks	Amorim et al. (2021)
Ibirapuitã	RS	5,942	Cropland, Native grasslands, Unpaved roads, Subsoil	Ramon (2021)
Uruguay	RS		Conceição River, Ibirapuitã River	Ramon (2021)
Guaíba lake	RS	85,139	Jacuí River, Caí Falls, Sinos River, Gravataí River	Tiecher et al. (2022)

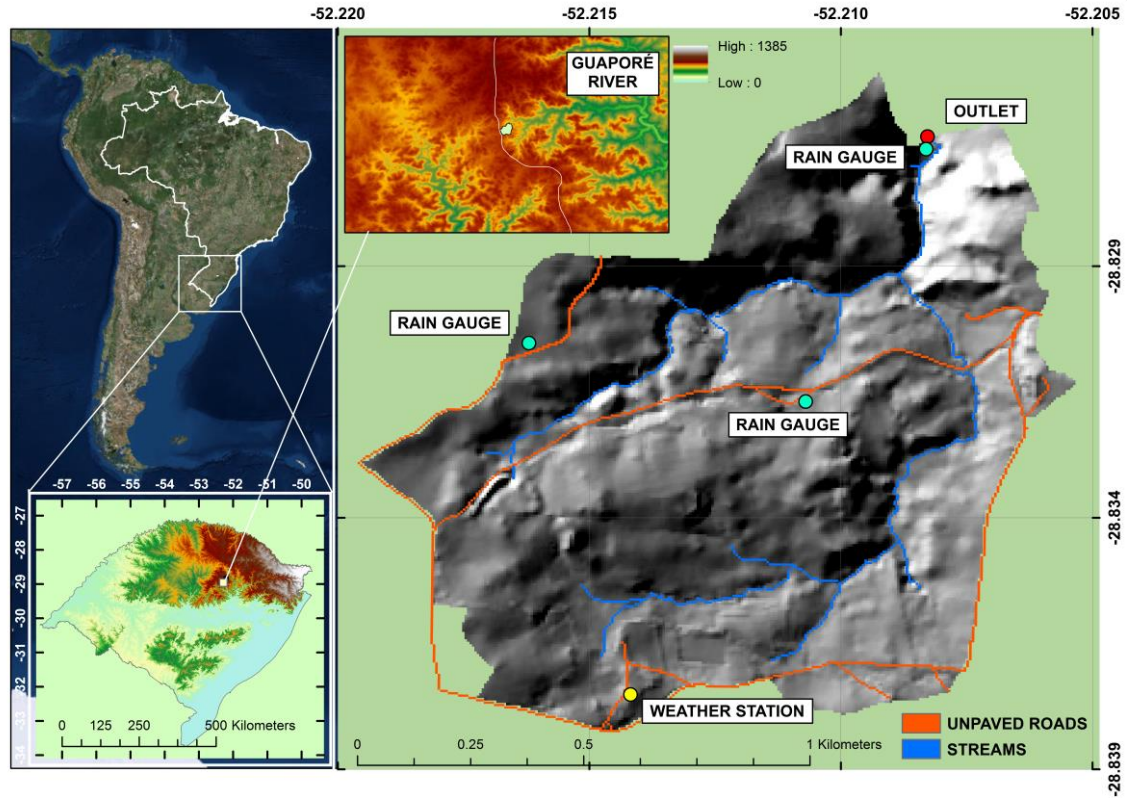
1090 RS, Rio Grande do Sul state; MG, Minas Gerais state; DF, Distrito Federal; PE, Pernambuco state.

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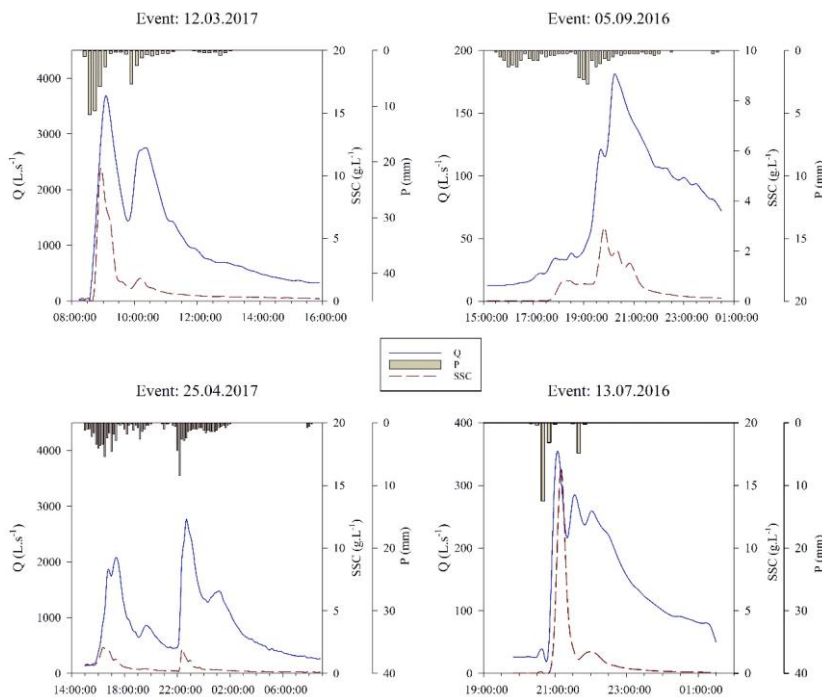
1093 **FIGURES**

1094 Figure 1. Location of the experimental Arvorezinha catchment in southern Brazil and
1095 monitoring network (adapted from Minella et al., 2018a).



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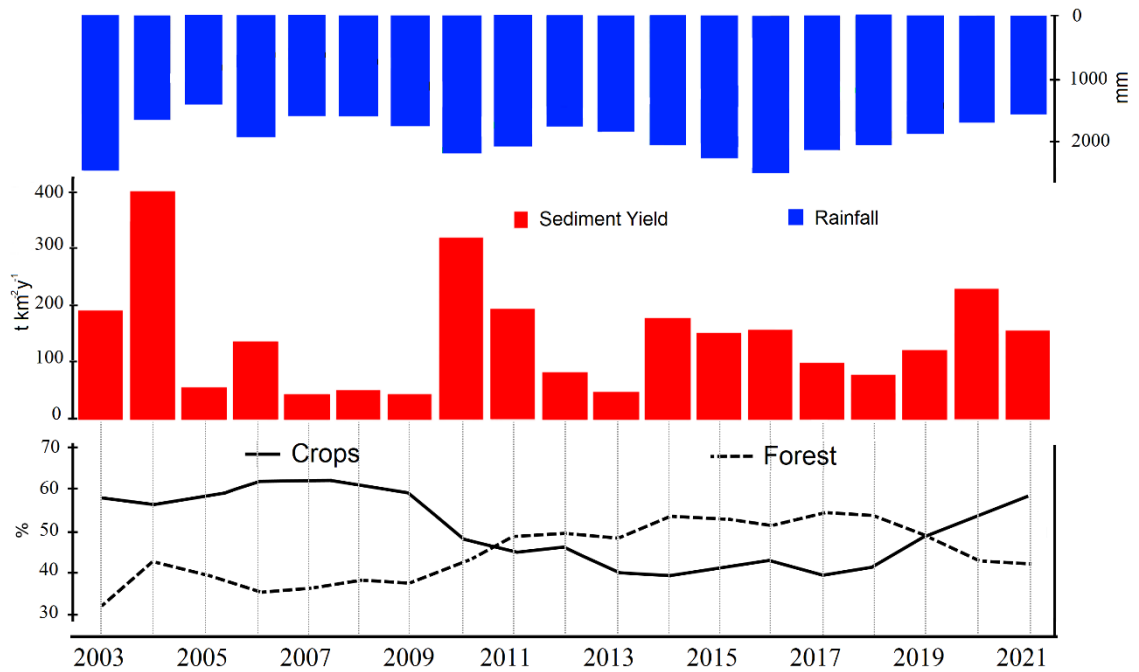
1097 Figure 2. Pluviographs, hydrographs, sedigraphs described in the experimental
1098 catchment of Arvorezinha during significant rainfall events (Menezes et al. 2020).



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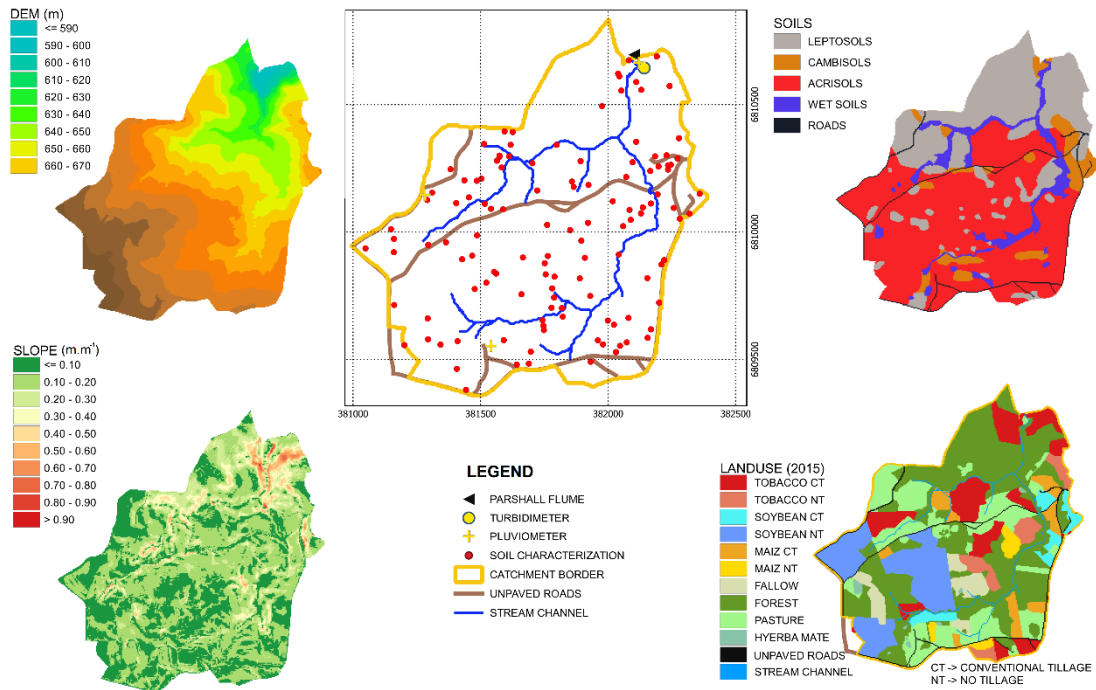
1101 Figure 3. Estimated annual sediment yield from 2002 to 2021 in the Arvorezinha
1102 catchment (Adapted from Minella et al., 2018a).



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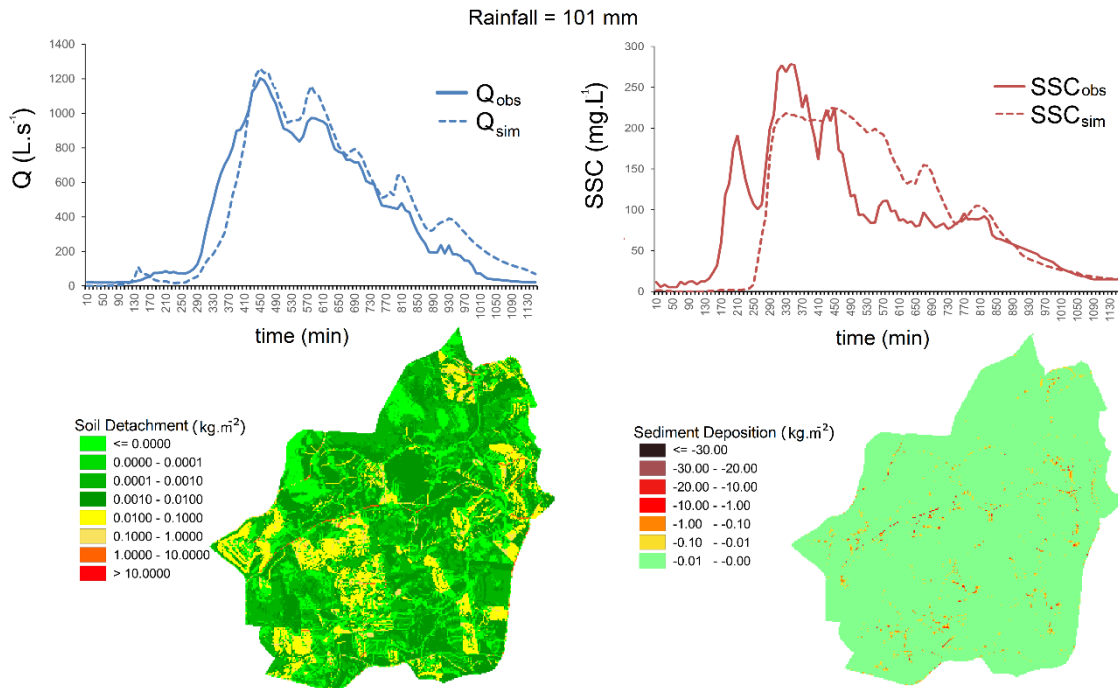
1105 Figure 4. Digital elevation model, slope, land use, and soil database used for modeling
1106 applications in the Arvorezinha catchment.



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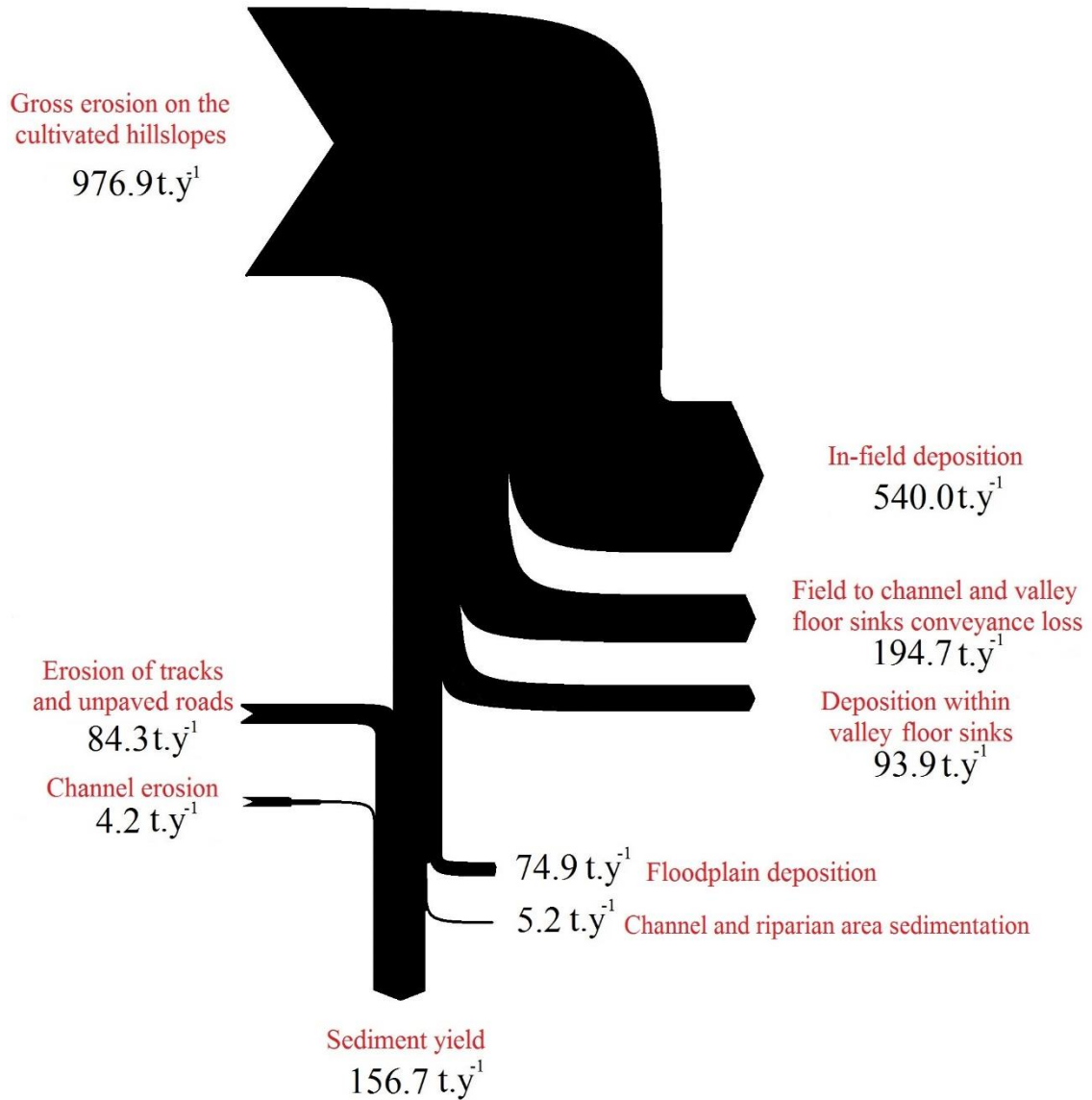
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1109 Figure 5. Typical results (hydrograph and sedigraph at the catchment outlet; soil
 1110 detachment and sediment deposition across the area) obtained from the LISEM model
 1111 in the Arvorezinha Catchment. Q_{obs} = streamflow observed, Q_{sim} = streamflow
 1112 simulated, SSC_{obs} = suspended sediment concentration observed, SSC_{sim} = suspended
 1113 sediment concentration simulated.



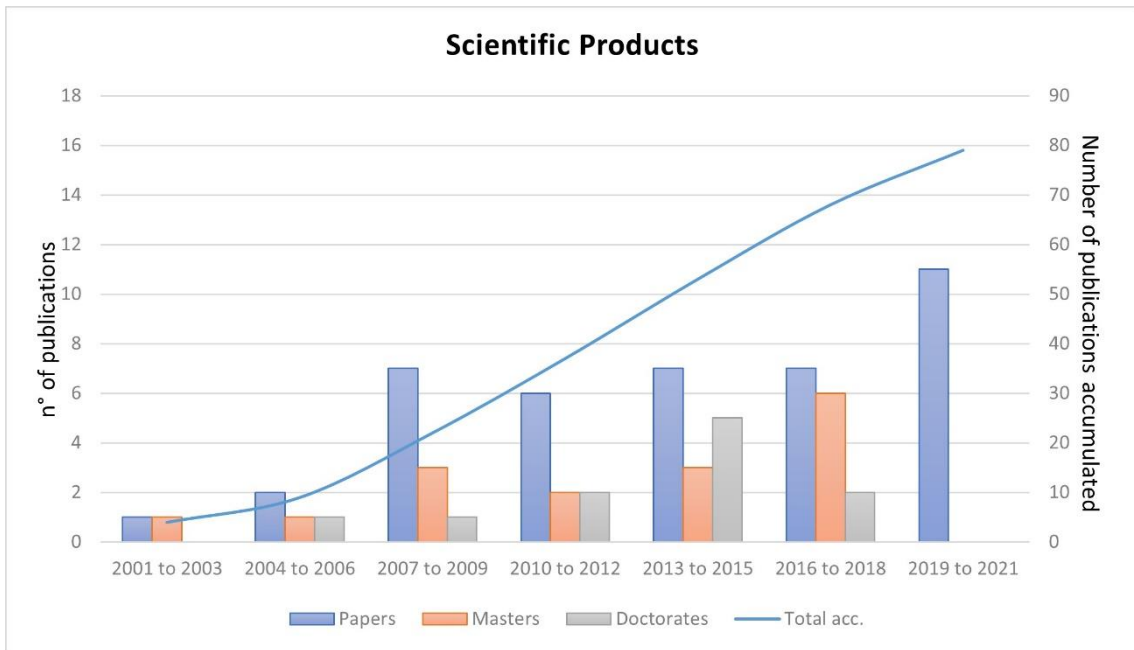
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1130 Figure 6. Sediment budget determination in the Arvorezinha catchment from coupling
 1131 the results of sediment yield monitoring, sediment source identification, and estimation
 1132 of erosion and deposition rates based on ^{137}Cs inventories (adapted from Minella et al.,
 1133 2008a).



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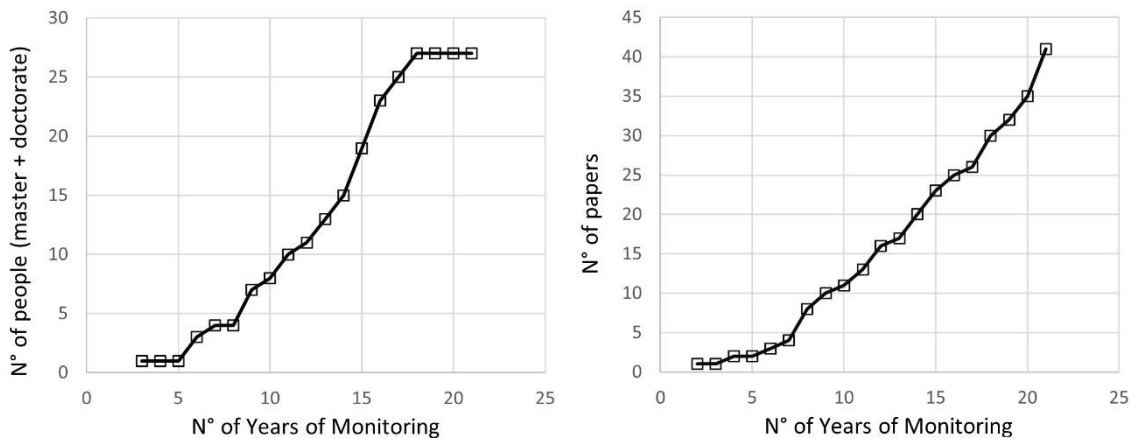
1143 Figure 7. Scientific and academic production during the 2001–2021 period in the
 1144 Arvorezinha experimental catchment.



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1147 Figure 8. Scientific and academic production over the years.



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SUPPLEMENTARY MATERIAL

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1152 **Challenges and recommendations for the installation and maintenance of**
1153 **experimental catchment based on the Arvorezinha experience**

1154 1 – Objectives:

1155 • Clearly define the objectives of the hydrologic monitoring project. Watershed
1156 monitoring should help solve practical local problems and explore technical
1157 challenges of scientific interest.

1158

1159 2 – Choosing a watershed to monitor and selection of appropriate scale:

- 1160 • The choice of monitoring section should be consistent with the project's
1161 objectives, the geomorphology of the streambed, the comfort and safety of the
1162 monitoring team, and ease of access during rainfall events.
- 1163 • Define the watershed's scale such that the flow rate and sediment concentration
1164 are sensitive to changes in soil use and management. The right scale is crucial to
1165 be able to observe the influence of the physical environment on the hydrologic
1166 processes of interest. The degree of spatial resolution of the controlling factors,
1167 for example, soil characteristics, relief, land use, and management, should be
1168 compatible with the modeling expectations and description of the key
1169 phenomena.
- 1170 • Plan to carry out the project for at least 10 years of monitoring. Results from the
1171 Arvorezinha experimental watershed demonstrated that 10 years were needed to
1172 show the effects of changes in soil management due to climactic variability
1173 (within and between years) and the occurrence of extreme weather events.
1174 Considering that most projects are funded for short periods (<5 years), it is vital
1175 to seek new sources of public or private funding.

1176

1177 3 – Monitoring strategy:

- 1178 • Define the basic set of variables necessary to express the selected phenomena
1179 and the best strategy to collect this information. Define acceptable margins of
1180 error incurred during data collection and processing to ensure that the
1181 information generated leads to reliable results.

1182 • Prioritize in-person hydrologic monitoring. One of the most important aspects of
1183 the Arvorezinha monitoring project involved stationing a technician at the
1184 monitoring site. This professional, trained as a hydrology technician, had the
1185 noble task of carrying out high quality data collection, as well as serving as a
1186 liaison between the researchers and farmers.

1187

1188 4 – Participation by the local community:

1189 • Define the role of the different stakeholders of the monitoring project (farmers,
1190 rural extension agents, monitoring team). Plan activities that allow for
1191 continuous integration and communication between the monitoring team and the
1192 local community. In the case of Arvorezinha, students at the local school became
1193 the most important link between the rural extension agents, the monitoring team
1194 and the farming families.

1195

1196 5 – Interdisciplinary collaboration:

1197 • Encourage interdisciplinary research activities. As part of the Arvorezinha
1198 monitoring project, professionals from different areas worked together to define
1199 the best strategies to characterize the environment, as well as the hydrologic and
1200 environmental monitoring. The main participants were water resources
1201 engineers, soil scientists, geographers, biologists and agronomists, permitting a
1202 rich convergence of ideas that worked together to improve the monitoring
1203 activities.

1204 • Encourage international cooperation. The Arvorezinha monitoring project
1205 created different opportunities to host well-known researchers who contributed
1206 substantially to the quality of the research conducted over the years, with many
1207 graduate students having the opportunity to complete internships overseas. In
1208 turn, many students from abroad were able to engage in research at the
1209 Arvorezinha catchment, thus advancing the monitoring methodology and
1210 understanding of the hydrogeomorphological processes under study.