Combining Sediment Source Tracing Techniques with Traditional Monitoring: The "Arvorezinha Catchment" Experience

Jean P G Minella, Gustavo H Merten, Alexandre Schlesner, Felipe Bernardi, Cláudia a P de Barros, Tales Tiecher, Rafael Ramon, Olivier Evrard, Danilo Rheinheimer Dos Santos, José Miguel Reichert, et al.

Combining Sediment Source Tracing Techniques with Traditional Monitoring: The "Arvorezinha Catchment" Experience

Jean P. G. Minella[1]*, Gustavo H. Merten[2], Alexandre Schlesner[1], Felipe Bernardi[1], Cláudia A. P. de Barros[3], Tales Tiecher[3], Rafael Ramon[4], Olivier Evrard[5], Danilo Rheinheimer dos Santos[1], José Miguel Reichert[1], Rutineia Tassi[6]

[1] Department of Soils, Federal University of Santa Maria

[2] Department of Civil Engineering, University of Minnesota-Duluth

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

[4] BASF SA, Environmental Fate - Regulatory Science Crop Protection

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

[6] Department of Sanitary and Environmental Engineering, Federal University of Santa Maria

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

Abstract

To truly understand the hydrologic and erosive processes that occur at the catchment scale regarding land use and soil management changes, intensive monitoring is required over a long period. Variables such as precipitation, flow rate, and suspended sediment concentration are the fundamentals needed to estimate sediment yield. However, in order to shed more light on the effects of soil management changes on sediment yield, traditional hydrologic monitoring techniques can be paired with sediment tracing to identify sediment sources. In addition, mathematical models that predict erosion and sediment yield can also help understand the dynamics of erosion and deposition between the hillslope and stream channel. Given the above, this paper provides an overview of almost 20 years of monitoring (2002–2021) in the Arvorezinha experimental catchment (1.23 km^2) located on the edge of the Brazilian meridional plateau in southern Brazil, which is subject to extreme erosion due to a combination of factors related to intensive agriculture and steep slopes. The catchment was selected as a study site to evaluate the effects of land-use changes and soil conservation management on hydrology and sediment yield. The text reviews the history of the study, synthesizes the main results, and describes the evolution of the monitoring techniques used while giving special attention to the fingerprinting approach. In addition, the article discusses the importance of catchment-scale studies for teaching, generating technical-scientific knowledge, and fostering collaboration between national and international research groups.

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

1. INTRODUCTION

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

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

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

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

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

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

2. MOTIVATIONS TO SET UP THE EXPERIMENTAL CATCHMENT MONITORING

In the early 2000s, the Government of Rio Grande do Sul (RS; the southernmost state of Brazil) created a project to improve land management as a key component of its program against rural poverty. The Rural Poverty Program, known as RS-Rural, aimed to implement public policies to improve the conditions of natural resources (soil, water, and vegetation) under degradation, local infrastructure (water supply, rural sanitation, and unpaved road improvement), and productive infrastructure (family agribusiness support) in poverty-stricken rural areas. The project aimed to enhance the rural communities' quality of life by increasing economic activities and improving natural resource management.

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

In order to evaluate the impacts of this promising project, the World Bank commissioned a study from the local government to quantify the socioeconomic impacts on natural resources. The method chosen to assess the effects on natural resources was based on installing four hydrological and soil quality monitoring units in different areas; these four monitoring units were chosen by EMATER-ASCAR, the UFSM (Federal University of Santa Maria) Department of Soil Science, and the UFRGS (Federal University of Rio Grande do Sul) Hydraulic Research Institute to represent areas with different geologies and soil characteristics. As a geographic unit, the researchers and extensionists selected ~1-km^2 catchments with first- to second-order drainage networks. Soil and water quality monitoring was then established to provide indicators of the impacts of the project's actions, and suspended sediment concentration and sediment yield were selected among the water quality indicators as they deliver sensitive indicators of the effectiveness of the project's soil and water conservation measures.

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

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

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

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

3. THE STUDY CATCHMENT

The Arvorezinha catchment is located on the edge of the Brazilian meridional plateau (28^{o}52'S and 52^{o}05'W) in southern Brazil (Figure 1). The catchment has an area of 1.23 km^2 and drains towards the Taquari River, one of the main tributaries of the Guaíba lake, which supplies water to over four million inhabitants of the Porto Alegre metropolitan area (roughly 37.7% of the inhabitants in the state) (IBGE, 2018). The Arvorezinha catchment altitude varies between 560 and 720 m. The topography is gently rolling in the upper third of the catchment with average slope gradients of ca. 7%. However, in its lower parts, the topography is characterized by shorter and steeper slopes (ca. 84%). The area is predominantly underlain by volcanic rocks, which weather to produce fertile Entisols and Inceptisols. The climate is mesothermal super-humid subtropical (i.e., Cfb), and the average annual rainfall is 1938 mm evenly distributed throughout the year. The catchment's physiographic characteristics were important for describing the processes of interest. The proximity of the crop fields to the drainage network and the narrow width of the riparian forest, for instance, determines the high connectivity between hillslope processes and the river channel. These characteristics made it possible to shed more light on the cause-and-effect relationships between the erosion processes at hillslopes and sediment yield at the river channel.

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

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

[Insert Figure 1]

4. THE PROCESSES OF INTEREST

4.1 Hydrological monitoring

The catchment was considered to provide the fundamental unit under investigation and relied on "sediment yield" as the main variable of interest. The studies have sought to improve monitoring techniques and hydrological modeling to enhance the design of soil and water conservation projects at the catchment scale. Monitoring required special attention to rainfall-runoff events. During rainfall events, the streamflow responses occur within minutes or a few hours, triggering soil detachment and sediment transport to the catchment outlet. Thus, the strategy of monitoring P, Q, and SSC needed to be efficient in the follow-up of significant events. The 10-minute interval was defined as the optimum data acquisition interval to describe the variables P, Q, and SSC and optimize data collection and organization, which proved to be enough to represent the variations and correctly describe the processes.

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

Collecting data of the events allowed researchers to analyze the effects of variations in land use and soil management as well as impacts related to climate on annual sediment yields, allowing the hydrological and erosive behavior of the catchment to be more accurately described. Interpreting medium and large magnitude hydrographs, which are responsible for the greatest soil losses, was fundamental to understanding runoff formation and propagation and sediment mobilization and transfer (sedigraphs). Four events are presented in Figure 2 to exemplify the response pattern of Q and SSC to rainfall events. To estimate SY throughout the monitoring period, a multiple linear regression analysis was used to quantify the relative contributions of different variables (climate, land use, and soil management). The long-term monitoring allowed us to interpret the combined effects of climate and anthropogenic activities on SY over the years (Figure 3) (Minella et al., 2009a; 2018).

[Insert Figure 2]

[Insert Figure 3]

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

4.2 Modeling runoff and sediment yield

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

In the Arvorezinha catchment, the mathematical modeling of SY became feasible because a large hydrological database was constructed and the compilation of information obtained in the field regarding changes in land use and soil management. In this way, the first five years (2002–2007) of monitoring were oriented toward obtaining consistent hydrological data. In the following phase (2008–2013), the mathematical models were used to better define the spatial representation of the factors related to the rainfall-runoff transformation and erosive and depositional processes associated with these events. Hence, great efforts were made to represent the physical environment, enabling physically-based models to be applied; the hydrological data gathering was also incremented, as previously described.

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

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

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

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

[Insert Figure 4]

[Insert Figure 5]

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

4.3 Linking catchment hillslope erosion processes into the drainage network

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

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

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

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

Hydrological monitoring combined with sediment tracing techniques demonstrates the individual variations of the source contributions, even if the absolute value of SY does not change significantly. Minella et al. (2008a) evaluated the change in SY in periods “without” and “with” soil conservation practices by combining sediment source identification with traditional monitoring. After the introduction of conservation practices (minimum till associated with cover crops), SY sharply decreased in croplands and unpaved roads and the contribution of channel erosion increased. The study showed that introducing conservation practices changed the emission pattern of the sources between field crops, unpaved roads, and stream channels due to the change in surface runoff behavior and transport capacity.

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

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

[Insert Figure 6]

In addition to the influence of land use and soil management, SY is strongly controlled by the magnitude of rainfall-runoff events. Obtaining information during different events throughout the year (inter-event pattern) captures the seasonal variability of land use and soil management. The inter-event pattern is also an alternative for verifying the pattern of source contributions. During rainfall-runoff events of different magnitudes, some sediment sources are activated while others are not. An example frequently reported in the literature is the increased relative contribution of sediment from unpaved roads during lower magnitude events and from catchment hillslopes during higher magnitude events (Minella et al., 2009b; Collins et al., 2010; Tiecher et al., 2017a).

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

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

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

"Start small"— this makes a lot of sense when evaluating the evolution of sediment tracing studies not only in Brazil but in the Arvorezinha catchment itself. The evolution of sediment fingerprinting research that started in the Arvorezinha catchment occurred following three main topics of investigation: (i) methodological advances, (ii) providing multiple lines of evidence regarding sediment dynamics, and (iii) expanding research across Brazil and increasing catchment scale and complexity.

5.1 Methodological advances

The Arvorezinha catchment has a relatively long history of monitoring. It is associated with a range of highly detailed information on soil type, land use, topography, and climate, among others, which was unprecedented in Brazil. In addition, the catchment has a long history of sediment fingerprinting studies using conventional tracers (geochemistry) based on analyzing chemical element concentrations analyzed in a highly detailed sampling grid of potential sources of sediment (in the order of >30 samples km^2) (Minella et al., 2008a, 2014). The spatial representation of unpaved roads and drainage channels as sediment sources were also important challenges in applying the technique in the Arvorezinha catchment. The sampling scheme for unpaved roads and stream channels as sediment sources followed a protocol developed for the catchment characteristics. The first strategy was to map the different soils that made up the roads and streams network. Subsequently, the sites with active erosion were identified in each soil unit of each source. The samples were composed of 20 sub-samples collected in homogenous stretches of approximately 20 m (Minella et al. 2008a).

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

Subsequently, some of these techniques, which were initially tested and validated in the Arvorezinha catchment, were also applied in other river catchments in southern Brazil, for example, Ramon et al. (2020), Valente et al. (2020), and Dambroz et al. (2022). The first two studies (Ramon et al., 2020; Valente et al., 2020) provided original approaches; they compared the results of spectroscopic tracers with those obtained with conventional methods (e.g., elemental concentrations, radionuclides). Valente et al. (2020) used color properties and visible ultraviolet spectroscopy in two small-paired catchments (one with commercial eucalyptus plantations [0.83 km^2] and the other with grassland used for livestock farming [1.10 km^2]) in the Brazilian Pampa biome. Ramon et al. (2020) used spectroscopy and color parameters in a much larger catchment (Conceição River [804 km^2]), with predominantly deep and strongly weathered Oxisols under no-till. In addition, the authors also successfully introduced magnetic properties to improve sediment source discrimination. More recently, Dambroz et al. (2022) in southern Brazil and Amorim et al. (2021) in a semi-arid region of northeastern Brazil used spectroscopy alone to investigate the contribution of sediment sources in the Guarda Mor (18.5 km^2) and Goiana (2857 km^2) catchments, respectively. Therefore, the lessons and tests carried out with alternative tracers in the Arvorezinha catchment were fundamental to validating the use of these reflectance spectroscopy techniques as a reliable, fast, and low-cost method without generating chemical residues to be used for quantifying the contribution of sediment sources in catchments across Brazil.

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

5.2 Providing multiple lines of evidence regarding sediment dynamics

The vast dissemination of sediment fingerprinting studies in recent years around the world is outstanding (Collins et al., 2020). Nevertheless, most of these studies are generally based on the sediment fingerprinting method, providing a unique line of evidence to better understand the dynamics of sediment supply in each catchment. Few researchers have focused on complementing sediment fingerprinting with catchment monitoring techniques and how multiple lines of evidence can help shed more light on sediment transport dynamics. Lessons from pioneering work in this combined approach are valuable even though it has not yet been widely adopted in sediment fingerprinting studies conducted across Brazil. Minella et al. (2008a) demonstrated the potential value of combining sediment source tracing techniques with traditional monitoring approaches when documenting the impact of improved land management on catchment SY. Minella et al. (2014) used 137Cs inventory measurements combined with SY measurements and sediment fingerprinting data to establish a provisional sediment budget for the Arvorezinha Catchment.

In the same line of research, Dambroz et al. (2022) used topographic attributes acquired from a digital elevation map and a spatially distributed erosion model (WaterSed) to simulate runoff, erosion, sediment yield, and sediment source contributions estimated using sediment fingerprinting based on near-infrared spectroscopy. The authors reported that combining different environmental diagnosis techniques effectively outlined the fragility of those areas where overland flow may accumulate and lead to accelerated soil degradation processes. Moreover, Tiecher et al. (2022) have also demonstrated that using sediment source tracing techniques, combined with sediment flux monitoring, can improve our understanding of the sediment source contributions to one of the largest lakes in South America: the Guaíba Lake (482 km^2). They used publicly available data from long-term monitoring of river discharge and SSC (1978–2019) combined with the shorter-term monitoring of chemical element concentrations in bed sediment (2000–2011) as geochemical tracers. The estimates of the sediment contributions from the four main tributaries (Jacuí, Caí, Sinos, and Gravataí rivers) were found to be similar for both approaches. These findings demonstrated that the sediment fingerprinting approach combined with sediment flux monitoring could provide a valuable means of estimating the respective sediment contributions from individual tributaries in large and complex delta systems and may provide a powerful tool to guide water resource management.

5.3 Expanding research across Brazil and increasing catchment scale and complexity

The first sediment fingerprinting study in South America was carried out in the Arvorezinha catchment, more precisely, in a sub-catchment with an area of only 0.57 km^2 (Minella et al., 2003). Since then, most studies on the contribution of sediment sources have focused on small catchments with surface areas <10 km^2, all located in Rio Grande do Sul State (Table 1). Gradually, the catchments' sizes have increased, and studies have spread to other Brazilian states (Minas Gerais, Pernambuco, and Distrito Federal). After 2014, some studies were also developed at an intermediate scale (catchment areas ranging from 10^1 to 10^2 km^2) (Miguel et al., 2014; Batista et al., 2019; Dambroz et al., 2022). In addition, between 2014 and 2020, sediment fingerprinting studies were carried out in catchments with a total area of between 800 and 1200 km^2 (Franz et al., 2014; Tiecher et al., 2018; Batista et al., 2019; Ramon et al., 2020). Nevertheless, research has only been carried out in catchments larger than 2000 km^2 since 2017 (le Gall et al., 2017; Tiecher et al., 2017c; Amorim et al., 2021). More recently, the target catchment area jumped to 5942 km^2 in a catchment experiencing a widespread land-use change in the last years (Ramon et al., 2020), where the conversion of natural grasslands into cropland accelerated soil erosion and sediment delivery to the river systems. In addition, two more tentative approaches have used the sediment collected in the tributary outlet as potential sources to estimate the contribution of sediment from these tributary catchments to that supplied to a larger drainage system, such as the Uruguay River (266,132 km^2) (Ramon, 2021) and the Guaíba Lake (85,139 km^2) (Tiecher et al., 2022).

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

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

[Insert Table 1]

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

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

[Insert Figure 7]

In the project’s early years (2001-2006), there were intense field activities. Besides the monitoring, field surveys were needed to characterize the soils, relief, land use, and soil management, which were essential for mathematical modeling. Despite the great efforts made to consolidate the monitoring structure, scientific production was low during this period.

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

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

[Insert Figure 8]

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

7. CONCLUDING REMARKS

A vast array of people conquered the interdisciplinarity of research conducted in the Arvorezinha catchment. Scientists, farmers, and rural extension staff, motivated by the interest in implementing the results obtained during the monitoring period, contributed to this project's success. By observing the advances that the Arvorezinha experimental catchment has provided to the community, we can emphasize the following points:

1 - Public investments in education and research generate incalculable returns in professional training and useful results for socioeconomic and environmental development.

2 - The importance of installing and maintaining experimental catchments for basic training in hydrology, development of modern environmental monitoring techniques, and improvement of mathematical modeling.

3 - The importance of using complementary techniques, such as the "sediment fingerprinting approach," along with traditional hydrological monitoring and mathematical modeling methods to better understand the link between hydrological and erosion processes in response to catchment land use and soil management changes.

4 - The importance of a long-term hydrologic monitoring period (frequently more than 10 years) to better evaluate the impacts of soil and water conservation projects considering that the adoption of conservationist practices by farmers is a gradual process and subject to setbacks, as in the Arvorezinha catchment.

5- The relevance of national and international scientific collaboration between national and international reference groups.

ACKNOWLEDGEMENTS

The authors would like to thank the farmers of Candido Brum for welcoming us and helping with data collection; Cléber Shuster, Cesar Burilli, and Edmar Valdir Streck from the Conservation Technical Assistance Program (EMATER-ASCAR) for supporting these farmers in implementing conservation practices; hydrology technicians Adair Giongo, Ademir Giongo, Christian Cardoso, and Joelma Murliki for their dedicated field and laboratory work; the researchers Fabiola Lopes, Nilvânia Aparecida Mello, Evelyn Janssens, Michele Moro, Clamarion Maier, Leandro Dalbianco, Gleidson Rieff, and Flavio Pereira Oliveira for their enthusiasm and persistence in carrying out their thesis projects in the Arvorezinha catchment; Professor Gerard Govers and all students and researchers for their partnership in the SOGLO project; Professor Robin Thomas Clarke for helping us with statistical models; Professor Elemar Antonino Cassol for conducting the soil erosion studies using rainfall simulator; Professors João Mielniczuk and Enilson de Sá for the soil quality studies carried out in the Arvorezinha catchment; Professors Desmond E. Walling and Arthur Horowitz for the permanent support and lessons offered for the development of research on monitoring and modelling of sediment yield in southern Brazil.

We would also like to thank Darci Silva and Sergio Rauber from SINDITABACO for their financial support of this project, and the public funding institutions that, over time, have significantly contributed to the continuity of the studies, in particular, the Coordination for the Improvement of Higher Education Personnel (CAPES), the Brazilian National Council for Scientific and Technological Development (CNPq), and the Research Foundation of the State of Rio Grande do Sul (FAPERGS).

REFERENCES

Amorim, F. F., da Silva, Y. J. A. B., Nascimento, R. C., da Silva, Y. J. A. B., Tiecher, T., Nascimento, C. W. A., Minella, J. P. G., Zhang, Y., Upadhayay, H. R., Pulley, S., & Collins, A. L. (2021). Sediment source apportionment using optical property composite signatures in a rural catchment, Brazil. Catena, 202, 105208. https://doi.org/10.1016/j.catena.2021.105208

Aulenbach, B. T., Hooper, R. P., van Meerveld, H. J. (Ilja), Burns, D. A., Freer, J. E., Shanley, J. B., Huntington, T. G., McDonnell, J. J., & Peters, N. E. (2021). The evolving perceptual model of streamflow generation at the Panola Mountain Research Watershed. Hydrological Processes, 35(4). https://doi.org/10.1002/hyp.14127

Baartman, J. E. M., Jetten, V. G., Ritsema, C. J., & de Vente, J. (2012). Exploring effects of rainfall intensity and duration on soil erosion at the catchment scale using openLISEM: Prado catchment, SE Spain. Hydrological Processes, 26(7), 1034–1049. https://doi.org/10.1002/hyp.8196

Barros, C. A. P. (2012). Comportamento hidrossedimentológico de uma bacia hidrográfica rural utilizando técnicas de monitoramento e modelagem. Master Thesis in Soil Science. Universidade Federal de Santa Maria, Santa Maria, RS.

Barros, C. A. P. (2016). Dinâmica dos escoamentos na modelagem da produção de sedimento em uma pequena bacia rural. 195 p. Doctoral Dissertation in Soil Science. Universidade Federal de Santa Maria, Santa Maria, RS.

Barros, C. A. P., Minella, J. P. G., Dalbianco, L., & Ramon, R. (2014a). Description of hydrological and erosion processes determined by applying the LISEM model in a rural catchment in southern Brazil. Journal of Soils and Sediments, 14(7), 1298–1310. https://doi.org/10.1007/s11368-014-0903-7

Barros, C. A. P., Minella, J. P. G., Tassi, R., Dalbianco, L., & Ottonelli, A. S. (2014b). Estimation of soil water infiltration at the catchment scale. Revista Brasileira de Ciencia Do Solo, 38(2). https://doi.org/10.1590/S0100-06832014000200020

Barros, C. A. P., Tiecher, T., Ramon, R., Santos, D. R. dos, Bender, M. A., Evrard, O., Ayrault, S., & Minella, J. P. G. (2020). Investigating the relationships between chemical element concentrations and discharge to improve our understanding of their transport patterns in rural catchments under subtropical climate conditions. Science of The Total Environment, 748, 141345. https://doi.org/10.1016/j.scitotenv.2020.141345

Barros, C. A. P., Govers, G., Minella, J. P. G., & Ramon, R. (2021a). How water flow components affect sediment dynamics modeling in a Brazilian catchment. Journal of Hydrology, 597, 126111. https://doi.org/10.1016/j.jhydrol.2021.126111

Barros, C. A. P., Minella, J. P. G., Schlesner, A. A., Ramon, R., & Copetti, A. C. (2021b). Impact of data sources to DEM construction and application to runoff and sediment yield modelling using LISEM model. Journal of Earth System Science, 130(1), 53. https://doi.org/10.1007/s12040-020-01547-1

Bastos, F., Reichert, J. M., Minella, J. P. G., & Rodrigues, M. F. (2021). Strategies for identifying pollution sources in a headwater catchment based on multi-scale water quality monitoring. Environmental Monitoring and Assessment, 193(4). https://doi.org/10.1007/s10661-021-08930-5

Batista, P. V. G., Laceby, J. P., Silva, M. L. N., Tassinari, D., Bispo, D. F. A., Curi, N., Davies, J., & Quinton, J. N. (2019). Using pedological knowledge to improve sediment source apportionment in tropical environments. Journal of Soils and Sediments, 19(9), 3274–3289. https://doi.org/10.1007/s11368-018-2199-5

BELSPO. (2016). The SOil system under GLObal change (SOGLO). Https://Www.Belspo.Be/Belspo/Fedra/Proj.Asp?L=en&COD=P7%2F24#descr.

Bender, M. A., dos Santos, D. R., Tiecher, T., Minella, J. P. G., de Barros, C. A. P., & Ramon, R. (2018). Phosphorus dynamics during storm events in a subtropical rural catchment in southern Brazil. Agriculture, Ecosystems and Environment, 261. https://doi.org/10.1016/j.agee.2018.04.004

Bernardi, F. (2018). Técnicas de separação do escoamento em pequena bacia rural. Master Thesis in Environmental Engineering. Universidade Federal de Santa Maria, Santa Maria, RS.

Beven, K. (2006). A manifesto for the equifinality thesis. Journal of Hydrology, 320(1–2), 18–36. https://doi.org/10.1016/j.jhydrol.2005.07.007

Beven, K., Heathwaite, L., Haygarth, P., Walling, D., Brazier, R., & Withers, P. (2005). On the concept of delivery of sediment and nutrients to stream channels. Hydrological Processes, 19(2), 551–556. https://doi.org/10.1002/hyp.5796

Bordas, M. P., & Walling, D. E. (1988). Sediment Budgets. IAHS Publ. 174.

Clarke, R. T. (2015). A bootstrap calculation of confidence regions for proportions of sediment contributed by different source areas in a 'fingerprinting' model. Hydrological Processes, 29(12), 2694–2703. https://doi.org/10.1002/hyp.10397

Clarke, R. T., & Minella, J. P. G. (2016). Evaluating sampling efficiency when estimating sediment source contributions to suspended sediment in rivers by fingerprinting. Hydrological Processes, 30(19). https://doi.org/10.1002/hyp.10866

Collins, A. L., Walling, D. E., Stroud, R. W., Robson, M., & Peet, L. M. (2010). Assessing damaged road verges as a suspended sediment source in the Hampshire Avon catchment, southern United Kingdom. Hydrological Processes, 24(9), 1106–1122. https://doi.org/10.1002/hyp.7573

Collins, A. L., Blackwell, M., Boeckx, P., Chivers, C.-A., Emelko, M., Evrard, O., Foster, I., Gellis, A., Gholami, H., Granger, S., Harris, P., Horowitz, A. J., Laceby, J. P., Martinez-Carreras, N., Minella, J., Mol, L., Nosrati, K., Pulley, S., Silins, U., … Zhang, Y. (2020). Sediment source fingerprinting: benchmarking recent outputs, remaining challenges and emerging themes. Journal of Soils and Sediments, 20(12), 4160–4193. https://doi.org/10.1007/s11368-020-02755-4

Dalbianco, L. (2009). Variabilidade espacial e estimativa da condutividade hidráulica e caracterização físico-hídrica de uma microbacia hidrográfica rural. Master Thesis in Soil Science. Universidade Federal de Santa Maria, Santa Maria, RS.

Dalbianco, L. (2013). Simulação hidrossedimentológica com o modelo LISEM em uma pequena bacia hidrográfica rural. 92 p. Doctoral Dissertation in Soil Science. Universidade Federal de Santa Maria, Santa Maria, RS.

Dalbianco, L., Ramon, R., de Barros, C. A. P., Minella, J. P. G., Merten, G. H., & Didoné, E. J. (2017). Sampling strategies to estimate suspended sediment concentration for turbidimeter calibration. Revista Brasileira de Engenharia

Agricola e Ambiental, 21(12). https://doi.org/10.1590/1807-1929/agriambi.v21n12p884-889

Dambroz, A. P. B., Minella, J. P. G., Tiecher, T., Moura-Bueno, J. M., Evrard, O., Pedron, F. A., Dalmolin, R. S. D., Bernardi, F., Schneider, F. J. A., & Cerdan, O. (2022). Terrain analysis, erosion simulations, and sediment fingerprinting: a case study assessing the erosion sensitivity of agricultural catchments in the border of the volcanic plateau of Southern Brazil. Journal of Soils and Sediments. https://doi.org/10.1007/s11368-022-03139-6

de Vente, J., Poesen, J., Arabkhedri, M., & Verstraeten, G. (2007). The sediment delivery problem revisited. Progress in Physical Geography, 31(2), 155–178. https://doi.org/10.1177/0309133307076485

de Vente, J., Poesen, J., Verstraeten, G., Govers, G., Vanmaercke, M., van Rompaey, A., Arabkhedri, M., & Boix-Fayos, C. (2013). Predicting soil erosion and sediment yield at regional scales: Where do we stand? Earth-Science Reviews, 127, 16–29. https://doi.org/10.1016/j.earscirev.2013.08.014

Du, P., & Walling, D. E. (2017). Fingerprinting surficial sediment sources : Exploring some potential problems associated with the spatial variability of source material properties. Journal of Environmental Management, 194, 4–15. https://doi.org/10.1016/j.jenvman.2016.05.066

Ebling, E. D. (2022). Monitoramento, dinâmica e modelagem hidrossedimentológica de duas bacias hidrográficas rurais com produção de leite e grãos. Doctoral Dissertation in Soil Science. Universidade Federal de Santa Maria, Santa Maria, RS.

Franz, C., Makeschin, F., Weiß, H., & Lorz, C. (2014). Sediments in urban river basins: Identification of sediment sources within the Lago Paranoá catchment, Brasilia DF, Brazil – using the fingerprint approach. Science of The Total Environment, 466–467, 513–523. https://doi.org/10.1016/j.scitotenv.2013.07.056

Fenicia, F., & McDonnell, J. J. (2022). Modeling streamflow variability at the regional scale: (1) perceptual model development through signature analysis. Journal of Hydrology, 605, 127287. https://doi.org/10.1016/j.jhydrol.2021.127287

Foster, I. D. L., Boardman, J., Evans, J. L., Copeland-Phillips, R., Vadher, A. N., Wright, S., Collins, A. L., & Manning, C. (2022). Anthropogenic sediment traps and network dislocation in a lowland UK river. Earth Surface Processes and Landforms, 47(1), 143–158. https://doi.org/10.1002/esp.5235

Her, Y., & Chaubey, I. (2015). Impact of the numbers of observations and calibration parameters on equifinality, model performance, and output and parameter uncertainty. Hydrological Processes, 29(19), 4220–4237. https://doi.org/10.1002/hyp.10487

Hessel, R., & Jetten, V. (2007). Suitability of transport equations in modelling soil erosion for a small Loess Plateau catchment. Engineering Geology, 91(1), 56–71. https://doi.org/10.1016/j.enggeo.2006.12.013

Instituto Brasileiro de Geografia e Estatística (IBGE) (2018). Síntese de indicadores sociais: uma análise das condições de vida da população brasileira 2018. Rio de Janeiro: 143 p. (Estudos e pesquisas. Informação demográfica e socioeconômica, n. 39.

Jetten, V. (2018). OpenLISEM Multi-Hazard Land Surface Process Model: Documentation e User Manual.

Jetten, V. G., de Roo, a P. J., & Favis-Mortlock, D. (1999). Evaluation of field - scale and catchment - scale soil erosion models. Catena, 3, 521–541.

Keesstra, S. D., Bagarello, V., Ferro, V., Finger, D., & Parsons, A. J. (2020). Connectivity in hydrology and sediment dynamics. Land Degradation & Development, 31(17), 2525–2528. https://doi.org/10.1002/ldr.3401

le Gall, M., Evrard, O., Dapoigny, A., Tiecher, T., Zafar, M., Minella, J. P. G., Laceby, J. P., & Ayrault, S. (2017). Tracing Sediment Sources in a Subtropical Agricultural Catchment of Southern Brazil Cultivated With Conventional and Conservation Farming Practices. Land Degradation and Development, 28(4). https://doi.org/10.1002/ldr.2662

Maier, C. (2013). Variabilidade intra-evento da origem das fontes de sedimentos em uma bacia hidrográfica rural. Doctoral Dissertation in Water Resources. Universidade Federal do Rio Grande do Sul, Porto Alegre, RS.

Menezes, D., Minella, J. P. G., & Tassi, R. (2020). Monitoring sediment yield for soil and water conservation planning in rural catchments. Environmental Monitoring and Assessment, 192(11). https://doi.org/10.1007/s10661-020-08670-y

Merten, G. H., & Minella, J. P. G. (2002). Qualidade da água em bacias hidrográficas rurais: um desafio atual para a sobrevivência futura. Agroecologia e Desenvolvimento Rural Sustentável, 3(4), 33–38.

Merten, G. H., & Minella, J. P. G. (2006). Impact on sediment yield due to the intensification of tobacco production in a catchment in Southern Brazil. Ciência Rural, 36(2), 669–672. https://doi.org/10.1590/S0103-84782006000200050

Merten, G. H., & Minella, J. P. G. (2014). Bedload flux in southern Brazilian basalt scarp. IAHS-AISH Proceedings and Reports, 367. https://doi.org/10.5194/piahs-367-185-2015

Merten, G. H., Capel, P. D., & Minella, J. P. G. (2014a). Effects of suspended sediment concentration and grain size on three optical turbidity sensors. Journal of Soils and Sediments, 14(7), 1235–1241. https://doi.org/10.1007/s11368-013-0813-0

Merten, G. H., Minella, J. P. G., Horowitz, A., & Moro, M. (2014b). Determinação da concentração de sedimentos em suspensão em rios com o uso de turbidímetro. CPRM e IPH-UFRGS.

Miguel, P., Dalmolin, R. S. D., Pedron, F. de A., Moura-Bueno, J. M., & Tiecher, T. (2014). Identificação de fontes de produção de sedimentos em uma bacia hidrográfica de encosta. Revista Brasileira de Ciência Do Solo, 38(2), 585–598. https://doi.org/10.1590/S0100-06832014000200023

Minella, J. P. G. (2003). Identificação de fontes de produção de sedimentos em uma pequena bacia rural. Master Thesis in Water Resources. Universidade Federal do Rio Grande do Sul, Porto Alegre, RS.

Minella, J. P. G. (2007). Utilização de técnicas hidrossedimentométricas combinadas com a identificação de fontes de sedimentos para avaliar o efeito do uso e do manejo do solo nos recursos hídricos de uma bacia hidrográfica rural no Rio grande do Sul. Doctoral Dissertation in Water Resources. Universidade Federal do Rio Grande do Sul, Porto Alegre, RS.

Minella, J. P. G., Merten, G. H., & Clarke, R. (2003). Identification of sediment sources in a small rural drainage basin. In Valentin Golosov, Vladimir Belyaev, & des E. Walling. (Eds.), Sediment Transfer through the Fluvial System. IAHS Publ. 288. (pp. 44–51). IAHS Press.

Minella, J. P. G., Merten, G. H., & Clarke, R. T. (2004). Identification of sediment sources in a small rural drainage basin. IAHS-AISH Publication, 288.

Minella, J. P. G., Merten, G. H., Reichert, J. M., & dos Santos, D. R. (2007). Identification and implications for soil conservation of sediment sources in catchment areas. Revista Brasileira de Ciencia Do Solo, 31(6).

Minella, J. P. G., Walling, D. E., & Merten, G. H. (2008a). Combining sediment source tracing techniques with traditional monitoring to assess the impact of improved land management on catchment sediment yields. Journal of Hydrology, 348(3–4), 546–563. https://doi.org/10.1016/j.jhydrol.2007.10.026

Minella, J. P. G., Merten, G. H., Reichert, J. M., & Clarke, R. T. (2008b). Estimating suspended sediment concentrations from turbidity measurements and the calibration problem. Hydrological Processes, 22(12). https://doi.org/10.1002/hyp.6763

Minella, J. P. G., Merten, G. H., Walling, D. E., & Reichert, J. M. (2009a). Changing sediment yield as an indicator of improved soil management practices in southern Brazil. Catena, 79(3), 228–236. https://doi.org/10.1016/j.catena.2009.02.020

Minella, J. P. G., Merten, G. H., & Clarke, R. T. (2009b). Fingerprinting method for identification of sediment sources in a rural watershed. Revista Brasileira de Engenharia Agrícola e Ambiental, 13(5).

Minella, J. P. G., Merten, G. H., & Magnago, P. F. (2011). Análise qualitativa e quantitativa da histerese entre vazão e concentração de sedimentos durante eventos hidrológicos. Revista Brasileira de Engenharia Agrícola e Ambiental, 15(12), 1306–1313. https://doi.org/10.1590/S1415-43662011001200013

Minella, J. P. G., Walling, D. E., & Merten, G. H. (2014). Establishing a sediment budget for a small agricultural catchment in southern Brazil, to support the development of effective sediment management strategies. Journal of Hydrology, 519(PB), 2189–2201. https://doi.org/10.1016/j.jhydrol.2014.10.013

Minella, J. P. G., Merten, G. H., Barros, C. A. P., Ramon, R., Schlesner, A., Clarke, R. T., Moro, M., & Dalbianco, L. (2018). Long-term sediment yield from a small catchment in southern Brazil affected by land use and soil management changes. Hydrological Processes, 32(2). https://doi.org/10.1002/hyp.11404

Moro, M. (2011). Avaliação do modelo LISEM na simulação dos processos hidrossedimentológicos de uma pequena bacia rural nas encostas basálticas do RS. Doctoral Dissertation in Water Resources. Universidade Federal do Rio Grande do Sul, Porto Alegre, RS.

Mutua, B. M., Klik, a., & Loiskandl, W. (2006). Modelling soil erosion and sediment yield at a catchment scale: the case of Masinga catchment, Kenya. Land Degradation & Development, 17(5), 557–570. https://doi.org/10.1002/ldr.753

Nadal-Romero, E., Peña-Angulo, D., & Regüés, D. (2018). Rainfall, run-off, and sediment transport dynamics in a humid mountain badland area: Long-term results from a small catchment. Hydrological Processes, 32(11), 1588–1606. https://doi.org/10.1002/hyp.11495

Poleto, C., Merten, G. H., & Minella, J. P. (2009). The identification of sediment sources in a small urban watershed in southern Brazil: an application of sediment fingerprinting. Environmental Technology, 30(11), 1145–1153. https://doi.org/10.1080/09593330903112154

Puttock, A., Macleod, C., Bol, R., Sessford, P., Dungait, J., Brazier, R. (2013) Changes in ecosystem structure, function and hydrological connectivity control water, soil and carbon losses in semi-arid grass to woody vegetation transitions. Earth Surface Processes and Landforms, 38(13), 1602-1611. https://doi.org/10.1002/esp.3455Ramon, R. (2021). Quantifying sediment source contributions in contrasted agricultural catchments (Uruguay River, Southern Brazil). Doctoral Dissertation in Soil Science. Universidade Federal do Rio Grande do Sul, Porto Alegre, RS.

Ramon, R., Minella, J. P. G., Merten, G. H., de Barros, C. A. P., & Canale, T. (2017). Kinetic energy estimation by rainfall intensity and its usefulness in predicting hydrosedimentological variables in a small rural catchment in southern Brazil. Catena, 148. https://doi.org/10.1016/j.catena.2016.07.015

Ramon, R., Evrard, O., Laceby, J. P., Caner, L., Inda, A. v., Barros, C. A. P., Minella, J. P. G., & Tiecher, T. (2020). Combining spectroscopy and magnetism with geochemical tracers to improve the discrimination of sediment sources in a homogeneous subtropical catchment. Catena, 195, 104800. https://doi.org/10.1016/j.catena.2020.104800

Reichert, J.M., Gubiani, P.I., Rheinheimer dos Santos, D., Reinert, D.J., Aita, C., Giacomini, S.J. (2022). Soil properties characterization for land-use planning and soil management in watersheds under family farming. International Soil and Water Conservation Research. https://doi.org/10.1016/j.iswcr.2021.05.003

Robinet, J., Minella, J. P. G., de Barros, C. A. P., Schlesner, A., Lücke, A., Ameijeiras-Mariño, Y., Opfergelt, S., Vanderborght, J., & Govers, G. (2018). Impacts of forest conversion and agriculture practices on water pathways in Southern Brazil. Hydrological Processes, 32(15). https://doi.org/10.1002/hyp.13155

Rodrigues, M. F., Reichert, J. M., Burrow, R. A., Flores, E. M. M., Minella, J. P. G., Rodrigues, L. A., Oliveira, J. S. S., & Cavalcante, R. B. L. (2018). Coarse and fine sediment sources in nested watersheds with eucalyptus forest. Land Degradation and Development, 29(8). https://doi.org/10.1002/ldr.2977

Rodriguez-Lloveras, X., Bussi, G., Francés, F., Rodriguez-Caballero, E., Solé-Benet, A., Calle, M., & Benito, G. (2015). Patterns of runoff and sediment production in response to land-use changes in an ungauged Mediterranean catchment. Journal of Hydrology, 531, 1054–1066. https://doi.org/10.1016/j.jhydrol.2015.11.014

Schlesner, A. A. (2017). Modelagem da produção de sedimentos em bacia hidrográfica rural sob diferentes equações de eficiência de desagregação do modelo erosivo LISEM. 80 p. Master Thesis in Soil Science. Universidade Federal de Santa Maria, Santa Maria, RS.

Silva, C. C., Minella, J. P. G., Schlesner, A., Merten, G. H., Barros, C. A. P., Tassi, R., & Dambroz, A. P. B. (2021). Unpaved road conservation planning at the catchment scale. Environmental Monitoring and Assessment, 193(9), 595. https://doi.org/10.1007/s10661-021-09398-z

Stolte, J., Liu, B., Ritsema, C. J., van den Elsen, H. G. M., & Hessel, R. (2003). Modelling water flow and sediment processes in a small gully system on the Loess Plateau in China. Catena, 54(1–2), 117–130. https://doi.org/10.1016/S0341-8162(03)00060-2

Tiecher, T. (2015). Fingerprinting sediment sources in agricultural catchments in Southern Brazil. Doctoral Dissertation in Soil Science. Universidade Federal de Santa Maria, Santa Maria, RS.

Tiecher, T., Caner, L., Minella, J. P. G., & Santos, D. R. dos. (2015). Combining visible-based-color parameters and geochemical tracers to improve sediment source discrimination and apportionment. Science of the Total Environment, 527–528, 135–149. https://doi.org/10.1016/j.scitotenv.2015.04.103

Tiecher, T., Caner, L., Minella, J. P. G., Bender, M. A., & dos Santos, D. R. (2016). Tracing sediment sources in a subtropical rural catchment of southern Brazil by using geochemical tracers and near-infrared spectroscopy. Soil and Tillage Research, 155, 478–491. https://doi.org/10.1016/j.still.2015.03.001

Tiecher, T., Caner, L., Minella, J. P. G., Pellegrini, A., Capoane, V., Rasche, J. W. A., Schaefer, G. L., & Rheinheimer, D. D. S. (2017a). Tracing sediment sources in two paired agricultural catchments with different riparian forest and wetland proportion in southern Brazil. Geoderma, 285. https://doi.org/10.1016/j.geoderma.2016.10.008

Tiecher, T., Caner, L., Minella, J. P. G., Evrard, O., Mondamert, L., Labanowski, J., & Rheinheimer, D. D. S. (2017b). Tracing Sediment Sources Using Mid-infrared Spectroscopy in Arvorezinha Catchment, Southern Brazil. Land Degradation and Development, 28(5). https://doi.org/10.1002/ldr.2690

Tiecher, T., Minella, J. P. G., Caner, L., Evrard, O., Zafar, M., Capoane, V., le Gall, M., & Santos, D. R. D. (2017c). Quantifying land use contributions to suspended sediment in a large cultivated catchment of Southern Brazil (Guaporé River, Rio Grande do Sul). Agriculture, Ecosystems and Environment, 237. https://doi.org/10.1016/j.agee.2016.12.004

Tiecher, T., Minella, J. P. G., Evrard, O., Caner, L., Merten, G. H., Capoane, V., Didoné, E. J., & dos Santos, D. R. (2018). Fingerprinting sediment sources in a large agricultural catchment under no-tillage in Southern Brazil (Conceição River). Land Degradation and Development, 29(4). https://doi.org/10.1002/ldr.2917

Tiecher, T., Ramon, R., Laceby, J. P., Evrard, O., & Minella, J. P. G. (2019). Potential of phosphorus fractions to trace sediment sources in a rural catchment of Southern Brazil: Comparison with the conventional approach based on elemental geochemistry. Geoderma, 337. https://doi.org/10.1016/j.geoderma.2018.11.011

Tiecher, T., Moura-Bueno, J. M., Caner, L., Minella, J. P. G., Evrard, O., Ramon, R., Naibo, G., Barros, C. A. P., Silva, Y. J. A. B., Amorim, F. F., & Rheinheimer, D. S. (2021). Improving the quantification of sediment source contributions using different mathematical models and spectral preprocessing techniques for individual or combined spectra of ultraviolet–visible, near- and middle-infrared spectroscopy. Geoderma, 384, 114815. https://doi.org/10.1016/j.geoderma.2020.114815

Tiecher, T., Ramon, R., de Andrade, L. C., Camargo, F. A. O., Evrard, O., Minella, J. P. G., Laceby, J. P., Bortoluzzi, E. C., Merten, G. H., Rheinheimer, D. S., Walling, D. E., & Barros, C. A. P. (2022). Tributary contributions to sediment deposited in the Jacuí Delta, Southern Brazil. Journal of Great Lakes Research. https://doi.org/10.1016/j.jglr.2022.02.006

Uzeika, T., Merten, G. H., Minella, J. P. G., & Moro, M. (2012). Use of the swat model for hydro-sedimentologic simulation in a small rural watershed. Revista Brasileira de Ciência Do Solo, 36(2). https://doi.org/10.1590/S0100-06832012000200025

Valente, M. L., Reichert, J. M., Legout, C., Tiecher, T., Cavalcante, R. B. L., & Evrard, O. (2020). Quantification of sediment source contributions in two paired catchments of the Brazilian Pampa using conventional and alternative fingerprinting approaches. Hydrological Processes, 34(13), 2965–2986. https://doi.org/10.1002/hyp.13768

Walling, D. E. (1983). The sediment delivery problem. Journal of Hydrology, 65, 209–237.

Walling, D. E. (1999). Linking land use, erosion and sediments yields in river basins. Hydrobiologia, 410, 223–240. https://doi.org/10.1007/978-94-017-2163-9

Walling, D. E. (2005). Tracing suspended sediment sources in catchments and river systems. Science of the Total Environment, 344(1-3 SPEC. ISS.), 159–184. https://doi.org/10.1016/j.scitotenv.2005.02.011

Walling, D. E. (2013). The evolution of sediment source fingerprinting investigations in fluvial systems. Journal of Soils and Sediments, 13(10), 1658–1675. https://doi.org/10.1007/s11368-013-0767-2

Walling, D. W., Woodward, J. C., & Nicholas, A. P. (1993). A multi-parameter approach to fingerprinting suspended-sediment sources. Tracers in Hydrology. Proc. International Symposium, Yokohama, 1993.

Walling, D. E., Collins, A. L., Sichingabula, H. M., & Leeks, G. J. L. (2001). Integrated assessment of catchment suspended sediment budgets: A Zambian example. Land Degradation and Development, 12(5), 387–415. https://doi.org/10.1002/ldr.461

Walling, D. E., & Fang, D. (2003). Recent trends in the suspended sediment loads of the world’s rivers. Global and Planetary Change, 39(1–2), 111–126. https://doi.org/10.1016/S0921-8181(03)00020-1

Walling, D. E., & Horowitz, A. (2005). Sediment Budget. IAHS Publ. 291.

World Bank. (2005). Natural resources management and rural poverty alleviation project Rio Grande do Sul, Report Number 36532. Retrieved from http://www.worldbank.org/en/research.

Ziemer, R. R., Lewis, J., Rice, R. M., & Lisle, T. E. (1991). Modeling the Cumulative Watershed Effects of Forest Management Strategies. Journal of Environmental Quality, 20(1), 36–42.

TABLE

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)

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

FIGURES

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

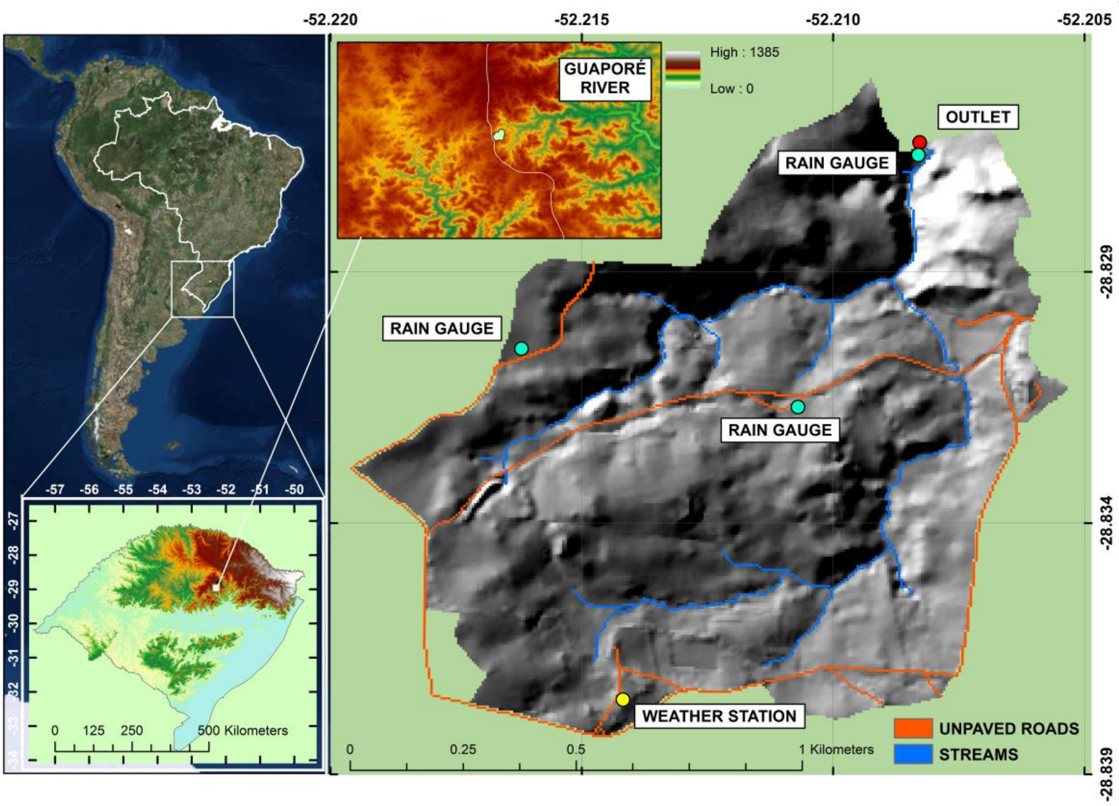


Figure 2. Pluviographs, hydrographs, sedigraphs described in the experimental catchment of Arvorezinha during significant rainfall events (Menezes et al. 2020).

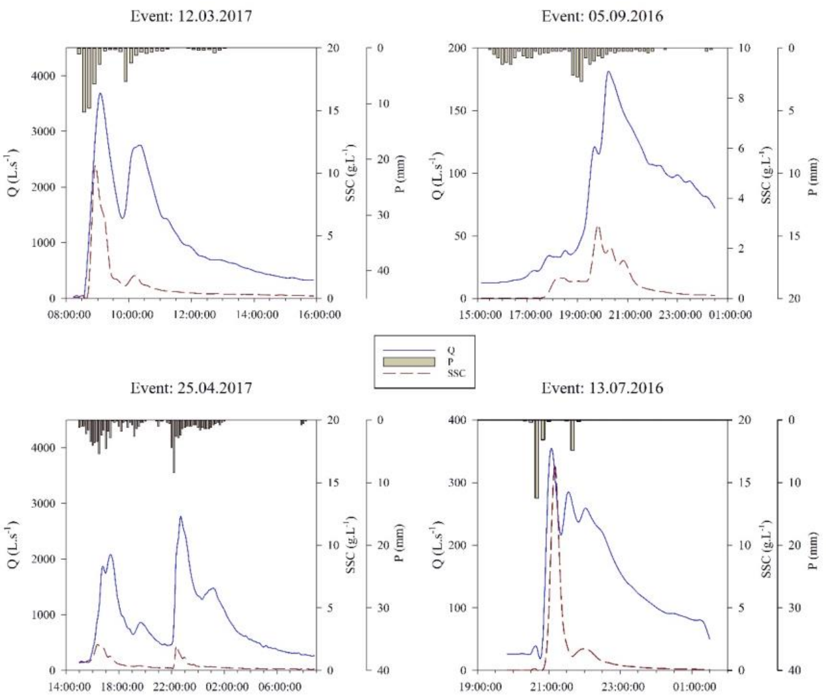


Figure 3. Estimated annual sediment yield from 2002 to 2021 in the Arvorezinha catchment (Adapted from Minella et al., 2018a).

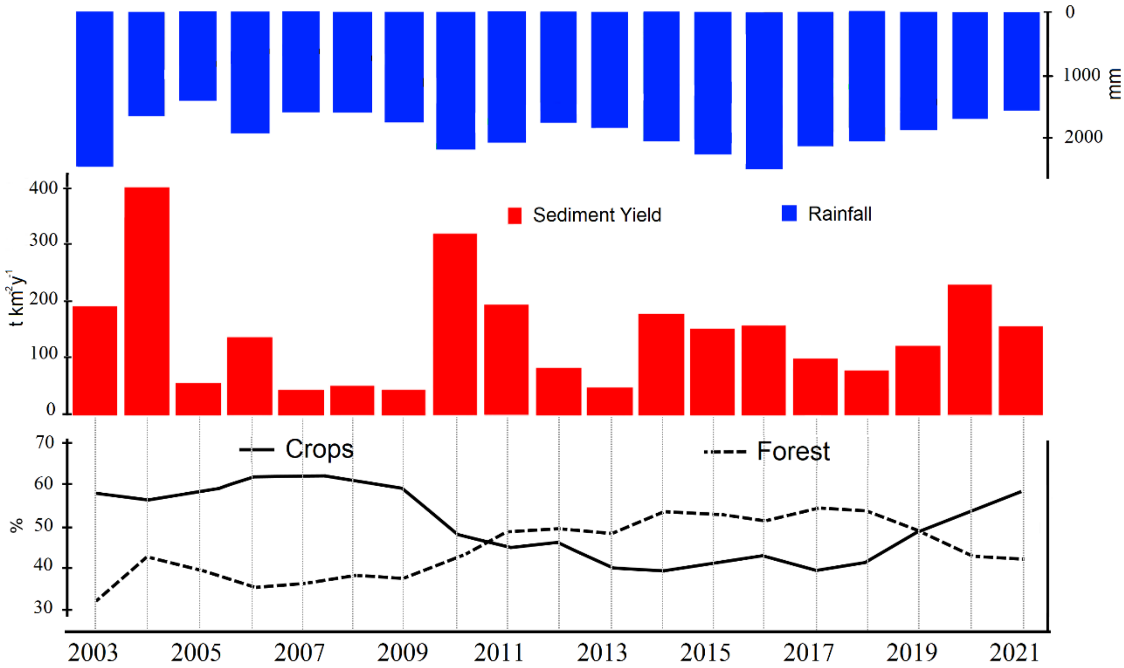


Figure 4. Digital elevation model, slope, land use, and soil database used for modeling applications in the Arvorezinha catchment.

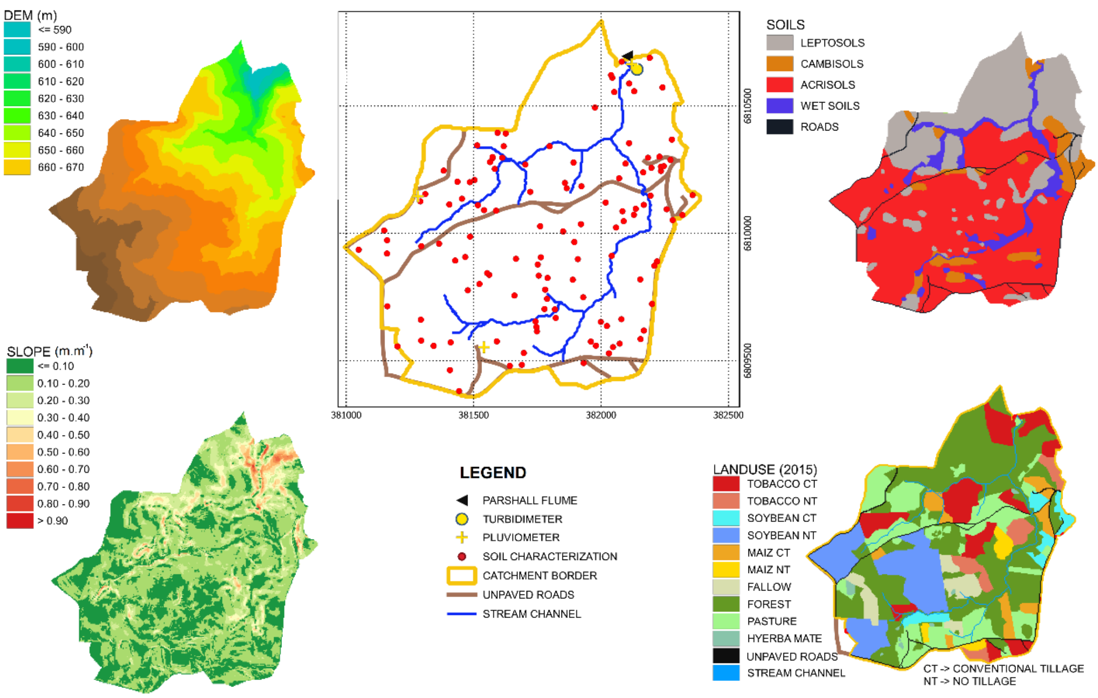


Figure 5. Typical results (hydrograph and sedigraph at the catchment outlet; soil detachment and sediment deposition across the area) obtained from the LISEM model in the Arvorezinha Catchment. Q_{obs} = streamflow observed, Q_{sim} = streamflow simulated, SSC_{obs} = suspended sediment concentration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

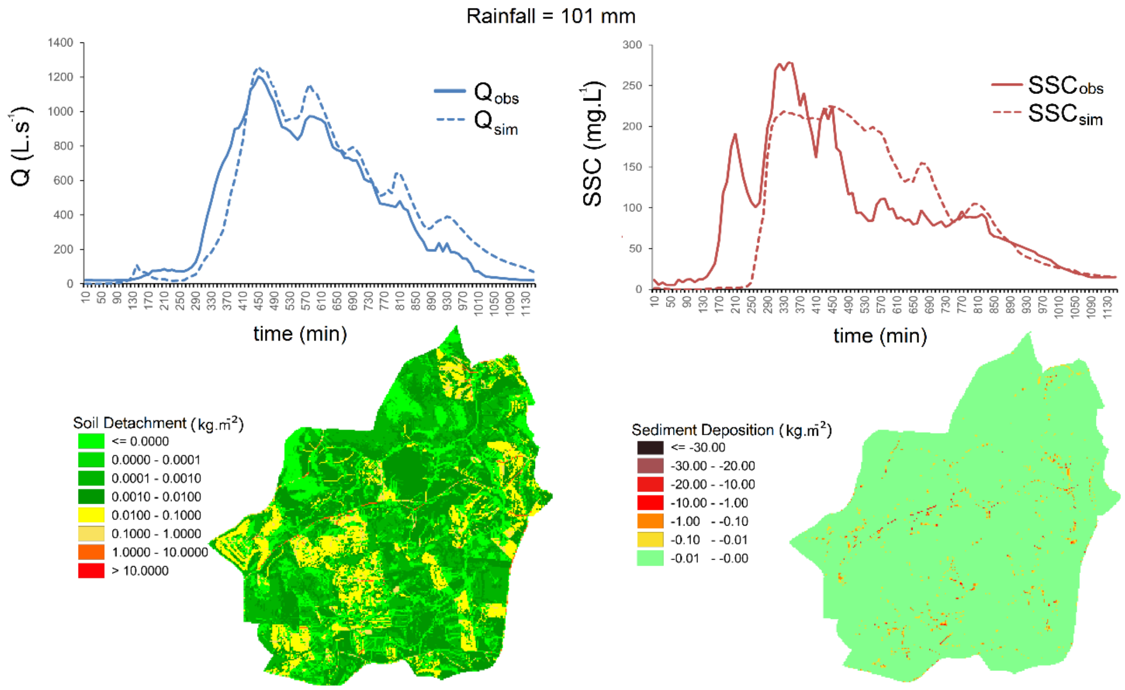


Figure 6. Sediment budget determination in the Arvorezinha catchment from coupling the results of sediment yield monitoring, sediment source identification, and estimation of erosion and deposition rates based on 137Cs inventories (adapted from Minella et al., 2008a).

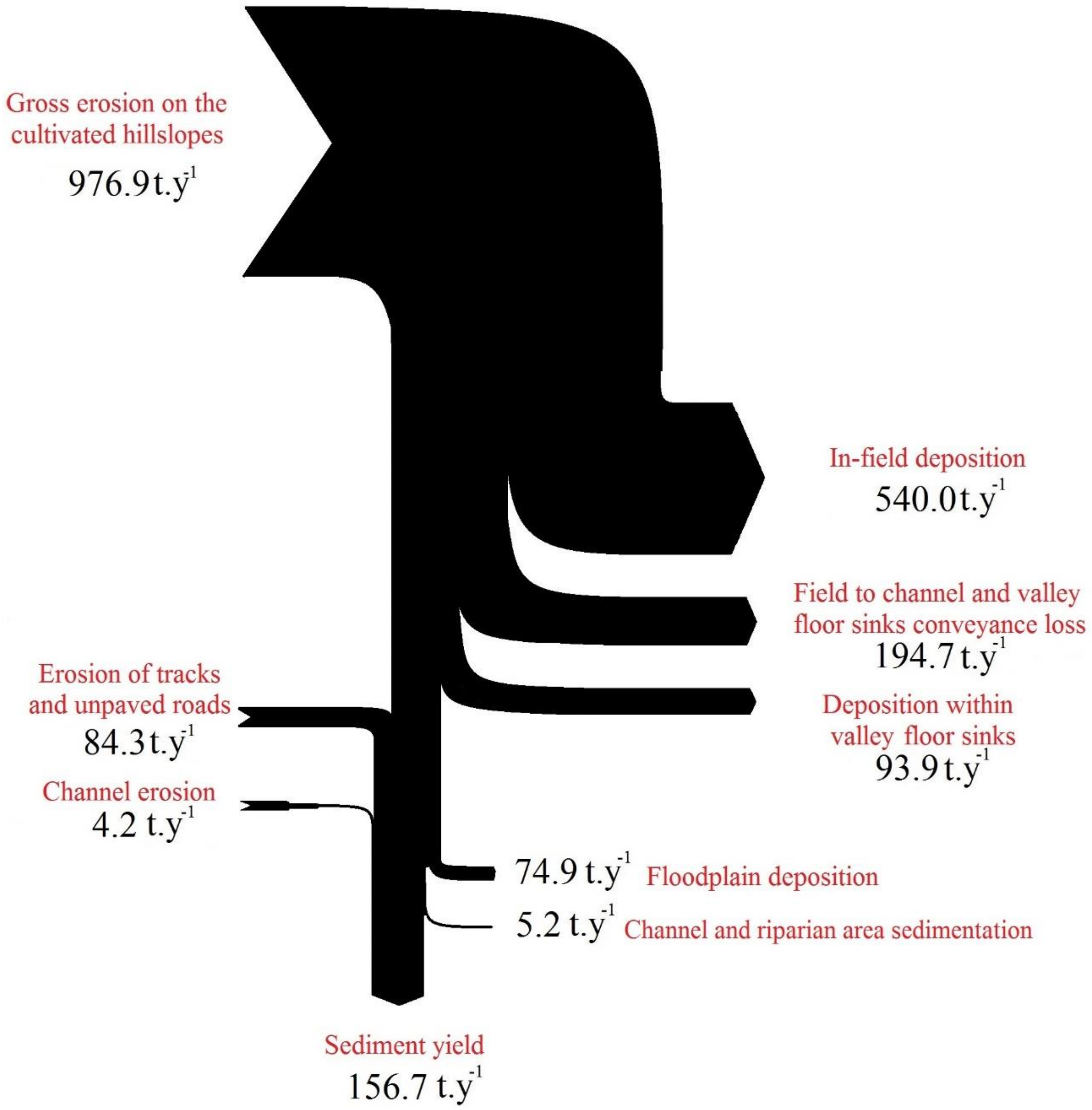


Figure 7. Scientific and academic production during the 2001–2021 period in the Arvorezinha experimental catchment.

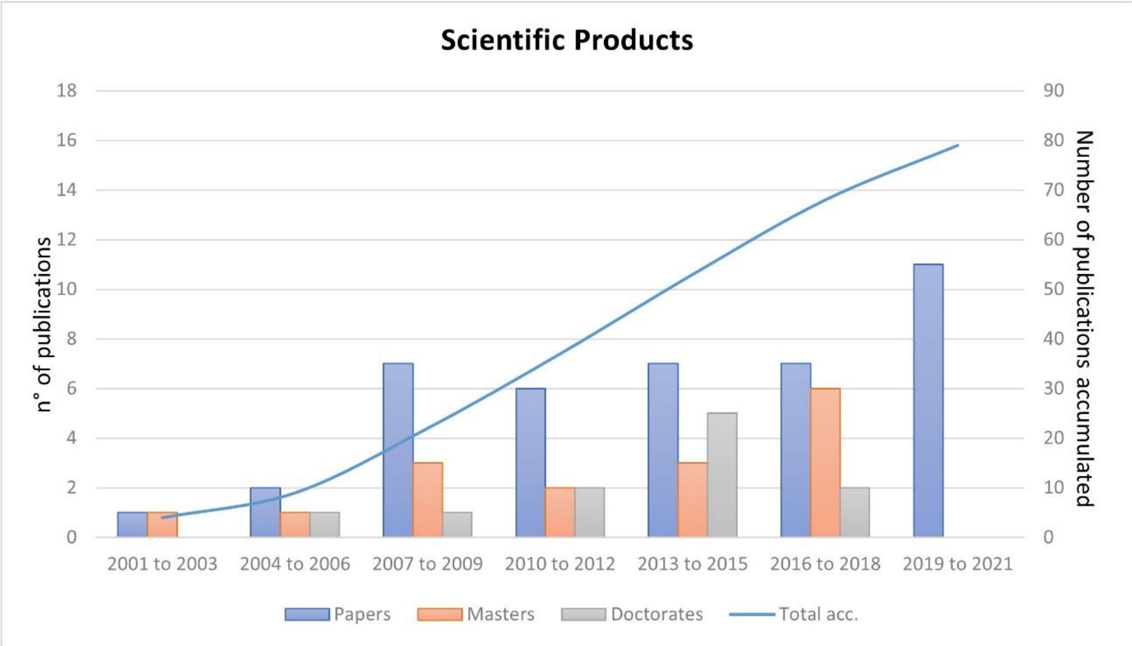
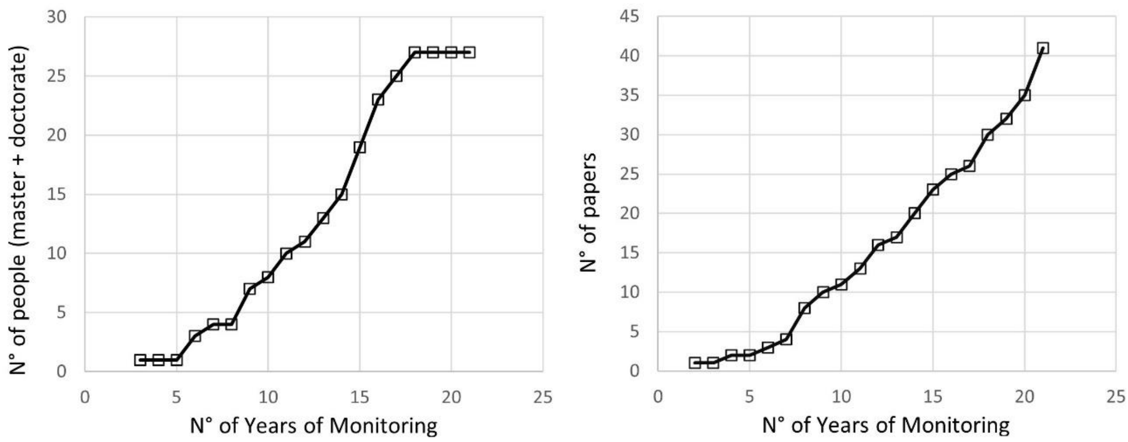


Figure 8. Scientific and academic production over the years.



SUPPLEMENTARY MATERIAL

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

1 – Objectives:

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

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

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

3 – Monitoring strategy:

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

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

4 – Participation by the local community:

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

5 – Interdisciplinary collaboration:

- Encourage interdisciplinary research activities. As part of the Arvorezinha monitoring project, professionals from different areas worked together to define the best strategies to characterize the environment, as well as the hydrologic and environmental monitoring. The main participants were water resources engineers, soil scientists, geographers, biologists and agronomists, permitting a rich convergence of ideas that worked together to improve the monitoring activities.
- Encourage international cooperation. The Arvorezinha monitoring project created different opportunities to host well-known researchers who contributed substantially to the quality of the research conducted over the years, with many graduate students having the opportunity to complete internships overseas. In turn, many students from abroad were able to engage in research at the Arvorezinha catchment, thus advancing the monitoring methodology and understanding of the hydrogeomorphological processes under study.