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Quantifying hydro-sedimentary transfers in a lowland tile-drained agricultural catchment

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ABSTRACT

Soil erosion, runoff and sediment connectivity are strongly impacted by anthropogenic features in lowland agricultural catchments. Among these landscape features, the role played by tile drainage on water and sediment transfers and hillslope-to-river connectivity in drained catchments remains poorly understood. This study quantified water and sediment transfers in a tile drained catchment of central France by combining high frequency rainfall, discharge and sediment concentration measurements at the outlet of a set of 10 tile drained plots (34 ha) and at the medium-sized (120 km²) catchment scale. Over the monitoring period, including a dry and a wet year compared to average conditions (one year with 112% of the mean annual rainfall and one year with 64% of the mean annual rainfall), 36 rainfall-flood events were recorded and analyzed. The high frequency analysis of water and sediment transfers in tile-drained plots showed a high seasonal variability and the occurrence of two transfer pathways in the soil column including the slow drainage of saturated soils and the occurrence of preferential flow pathways through the soil column. Indeed, 13 of the 36 recorded flood events showed hydrographs with two components, reflecting these two pathways: slow transfers in the soil columns and fast transfers through soil macropores and/or cracks. Indeed, at the beginning of the flood event, a high-magnitude peak overlaid on the hydrograph. On average, this fast peak contributed 15% of the water and sediment fluxes. The sediment dynamics in tile drains was suggested to depend on sediment storage and exhaustion processes occurring in the tile drain network.

1. Introduction

In Europe, agricultural landscapes were strongly modified following WWII to increase agricultural productivity through the removal of hedges, land consolidation and stream redesigning programs (Souchère et al., 2003; Evrard et al., 2010). The agricultural areas were also extended in lowland areas with the installation of tile drainage systems to convert wetlands into arable land. A review conducted by Montagne et al. (2009) demonstrated that these changes may act as geomorphic agents, which outlines the need to consider their role in catchment sediment dynamics. Installing tile drainage systems may have extensive environmental implications (Blann et al., 2009) because they may increase transfers of sediments from plots to rivers, which may have deleterious impacts on downstream environments (Owens et al., 2005; Kemp et al., 2011). Indeed, tile drainage creates new pathways for water, sediment and associated pollutants resulting in the loss of on-site nutrients such as phosphorous (Ulen and Persson, 1999; Macrae et al., 2007; Ulen et al., 2012). Furthermore, tile drains may also lead to off-site impacts including the enhanced export of pesticides (Kladivko et al., 2001). A specific problem occurring in these drained systems is associated with the fact that fluxes occurring in tile drains may bypass soil conservation measures (e.g. grass buffer strips) designed to prevent runoff and sediment transfers from cultivated land to the river channel (Le Bissonnais et al., 2004). These fluxes are therefore directly delivered to the river systems, resulting in an increased connectivity between plots and river systems, which may directly affect the water quality ( Rozemeijer et al., 2010). Moreover, it was demonstrated that a direct connection between the soil surface and tile drainage systems may occur.
(Akay and Fox, 2007; Frey et al., 2016), resulting in the limited retention and degradation of contaminants within the soil column (Stone and Wilson, 2006).

So far, most studies dealing with water and sediment transfers from tile drainage have been conducted at the plot scale (e.g. Turunen et al., 2013; Muma et al., 2016). They demonstrated that suspended sediment concentrations in subsurface drain flows could exhibit large variations and represent a large proportion of sediment fluxes (Deasy et al., 2009). Experimental studies were designed to investigate this issue both in the field and in the laboratory (e.g. Turtola et al., 2007; Van Den Bogaert et al., 2013). For instance, Uusitalo et al. (2001) measured concentrations ranging from 540 to 1240 mg l\(^{-1}\). Chapman et al. (2005) measured concentrations up to 2600 mg l\(^{-1}\). Based on this extensive research, very detailed numerical models were developed to simulate water and sediment transfers in drained plots (Warsta et al., 2013; Turunen et al., 2017). However, the role of preferential flows in the transfers of water, associated fertilizers and pesticides in drained systems remains unclear (Nagy et al., 2020a, 2020b). Moreover, the upsampling of these results from the plot to the catchment scales remains unresolved to date (De Vente and Poesen, 2005; Evrard et al., 2008; Delmas et al., 2012; Fiener et al., 2019). There is a lack of quantitative assessments of the impacts of tile drainage on water and sediment fluxes at the catchment scale, despite the fact that previous studies outlined the need to monitor drained catchments in order to improve our understanding of these preferential transfer pathways (Li et al., 2010; Hansen et al., 2013; King et al., 2014).

Previous studies investigating sediment transfers in tile drained catchments mainly relied on sediment fingerprinting approaches (Russell et al., 2001; Walling et al., 2002; Walling and Collins, 2008; Foucher et al., 2015; Le Gall et al., 2017). This technique consists in the measurement of conservative properties in potential sources and in sediment collected in the main river to quantify the respective contributions of these potential sources to the material transiting the river (Haddachi et al., 2013; Collins et al., 2017). They demonstrated that contributions from tile drains may be very variable, even at the flood event scale. However, these studies often combined tile drains with other sediment sources (e.g. channel banks in Cooper et al., 2015 or surface cropland in Foucher et al., 2015), underlining the complexity and the variety of processes involved in sediment transfers from tile drains.

In contrast, very few studies quantified water and sediment transfers from tile drains at the catchment scale based on high resolution (<15-minutes time step) drain and river monitoring, although the importance of quantifying these fluxes at very detailed temporal resolutions was demonstrated in contrasted environmental contexts (Meybeck et al., 2003; Navratil et al., 2011; De Girolamo et al., 2015). Although King et al. (2014) quantified water transfers from multiple tile drains with a high temporal resolution and evaluated their contribution to the entire catchment water budget, they did not measure suspended sediment fluxes. Cooper et al. (2015) combined high temporal resolution rainfall and water monitoring with sediment fingerprinting to construct time...
series of tile drain contributions. They however restricted their analysis to eight rainfall events only and did not quantify sediment fluxes with a high frequency. Grangeon et al. (2017) quantified water and sediment dynamics with a high temporal resolution at both the drained plot and the catchment scales, in an area where 41% of the surface is drained. They measured concentrations ranging from a few to 1600 mg l$^{-1}$, and estimated fluxes from tile drains to represent 0–63% of the catchment fluxes, with a mean of 13%. They also hypothesized that sediment fluxes mainly consisted of the flush of material stored in channels, but did not analyze the potential sediment storage in tile drains. However, their analysis was restricted to data from a single tile drain, which may lead to representativity issues and prevent the extrapolation of their results to larger and/or contrasted catchments. The objective of the current study was therefore to analyze the tile drain functioning, based on a set of drained plots to increase the analysis representativity. In particular, the processes leading to the seasonal and flood event scale variations in water and suspended sediment dynamics will be analyzed. To this end, water and suspended sediment dynamics at the outlet of multiple tile drains were monitored with a high temporal resolution (10 minute time step) over two contrasted hydrological years.

2. Materials and methods

2.1. The Bonnée River catchment

The Bonnée catchment is a medium-sized (120 km$^2$ at the monitoring station) headwater catchment tributary of the Loire River (France), mainly covered with cropland and forest. Forest dominates in catchment upper parts while lower parts are mainly covered with cropland (Fig. 1a). Wheat, maize, sugar beet, rapeseed and sunflower are the main crops cultivated in the region. The tile drained area is ranging from 30% to 50% of the utilized agricultural land in this part of France (Tournebize et al., 2020; Vincent, 2020). Elevation ranges from 103 to 176 m. Catchment topography is mainly...
and 7.1%, respectively, calculated from a 5-m resolution DEM. Highest steps: slope first, fifth (median) and ninth deciles amount to 0.3%, 1.7% composed of a sequence of three plateaus, separated by steeper gradient the Bonn. Temperate (Cfb) according to the Köppen-Geiger climate classification (Peel et al., 2007; Beck et al., 2018) with mean monthly temperatures ranging from 3°C to 18°C. The mean annual rainfall amounts to 637 mm at the nearby Orléans station, according to the national weather service, based on 30-year records (1981–2010). Monthly means are ranging from 45 mm to 65 mm, with higher values recorded from October to December and in May, and lower values recorded during summer.

2.2. River channel redesigning and tile drain network

The river channel was channelized between 1960 and 1970. The goal was to reduce the water transfer time to the outlet to decrease soil saturation, increase the agricultural productivity and reduce the inundation risk (Spaling and Smit, 1995). Consequently, the original (i.e. natural) river channel was disconnected (the natural water channel became higher than the redesigned one) and abandoned. To redirect the water flow into the original river channel and initiate the ecological restoration of the river to comply with the European Water Framework Directive, a small dam built between 1960 and 1970 was enhanced (up to 1.90 m) in 2013 (Fig. 1b).

It increased the water height in the upstream river section and resulted in water flowing both within the natural and the redesigned channels. However, it also increased the water height above some of the tile drains outlet, which made them inoperative. Therefore, a unique manmade, sewer-like network was installed to allow tile drain functioning, collecting water flowing from a set of 10 fields equipped with tile drains, covering a surface area of 34 ha (Fig. 2a). At the outlet of this network, water and sediment were collected in a sump (Fig. 2b). They were then pumped up into a wetland in order to trap sediment and contaminants before supplying ‘clean’ water to the river network. This sewer network therefore completely isolated tile drain fluxes from the river flow, providing a unique opportunity to monitor water and sediment fluxes from a set of tile drained cultivated fields during both baseflow and flood events.

Tile drain characteristics were variable across the set of fields monitored in the current research. They were all made of perforated PVC pipes. The pipe diameters ranged from 45 to 700 mm, and they were buried between 30 cm and 1.8 m below the soil surface.

2.3. Hydrological monitoring station

Two monitoring stations were installed to measure the water and sediment fluxes in both the Bonnée River and in the tile drain network. The river station was installed next to the tile drain network (Fig. 3) and was located 1 km upstream of the dam.

Each station was equipped with a water height (Nivelco Nivopress NKK) and a turbidity probe (Neotek Ponsel, 0–4000 NTU). An automatic sampler (Teledyne ISCO 3700) was used to collect river water and suspended sediment samples, mainly during flood events. An automatic pluviometer (Précis Mécanique 3029) was installed to monitor rainfall. Water height, turbidity and rainfall were monitored with a 10-minute resolution from September 2017 to July 2019. Because of several technical problems (e.g. probe failures), only the period from December 2017 to July 2019 was investigated in the current research.

2.3.1. Water discharge measurements in the main river

In the river, 11 streamflow measurements were performed during low and high flow periods in order to derive relationships to convert water height into discharge. However, a simple least square regression between water height and discharge did not allow fitting the relationship. High flows were underestimated, which was problematic because they transport most of the sediment fluxes (Navratil et al., 2011). A non-linear fitting procedure taking into account streamflow measurement uncertainties was therefore developed and resulted in a rating curve able to capture the highest discharges. The detailed procedure and the corresponding rating curve are provided as supplementary material.

When the highest storm event occurred (mid-February 2017 and during a large event in July 2018), the dam was opened by the local authorities to prevent flooding. In both cases, the water height time series was linearly interpolated when the dam was opened. The water height time series was not considered for analysis in February 2017. In July 2018, as the dam opening was performed during the falling limb of the hydrograph, the event was considered for analysis.

2.3.2. Water discharge measurements at the tile drain network outlet

Because of a low water height in the tile drain network and limited probe resolution (respectively in the order of 1–10 cm with 1 cm resolution), water height was measured in the sump, collecting fluxes from the entire tile drainage network. Due to fast water height variations, especially during flood events, it was monitored with a 15-second time step. The water volume time series in the sump, resulting from both tile drain network discharge and the sump pumping, was estimated from water height time series using the well-defined geometry of the sump (Fig. 2c). The volume calculated during the rising limb provided water input from the tile drain network, while the falling limb (resulting from pumping) were removed. Consequently, the discharge time series was then interpolated at a 10-minute time step to match the recording time step of the other measurements.

2.4. Soil and sediment sampling and analysis

2.4.1. Suspended sediment sampling and analysis

Suspended sediment was sampled using the ISCO 3700 device based on water level thresholds and time intervals during flood events, both in the tile drain network and in the Bonnée River. This procedure was adapted based on the monitored water level before a forecasted flood
event. In general, it consisted of one sampling per hour when the water level increased by more than 5 cm. The sampled water volume was fixed at 500 ml, although small (±10 ml) variations were measured. Therefore, the volume was systematically measured in the laboratory. River water was filtered with 0.45 µm-mesh filters and oven-dried at 105 °C for 24 h to obtain suspended sediment concentrations. These measurements were used to establish a suspended sediment concentration-turbidity rating curve. It was used to convert turbidity into suspended sediment concentration time series. The turbidity-concentration relationship was good for the Bonnée river and the tile drain network \( (R^2 = 0.93, n = 93 \text{ and } R^2 = 0.88, n = 44, \text{ respectively}) \). The sample concentrations were comprised between 8 and 3100 mg·l\(^{-1}\) for the Bonnée river. Due to technical issues (flood event flashiness and noise on the raw measured turbidity), sample concentrations for the tile drain network varied between 3 and 210 mg·l\(^{-1}\). Consequently, the concentration was extrapolated for less than 6% of the monitoring period.

2.4.2. Soil surface observations

Finally, during the two-year monitoring period, a monthly visual inspection of the soil surface was performed on the drained plots to document the density of the soil cover by vegetation, crusting stage, surface roughness and the occurrence of soil cracks, as all these characteristics were shown to control the runoff and erosion behavior of cultivated plots (Cerdan et al., 2002).

2.5. Flood event separation

Flood events were defined according to the methodology presented in Grangeon et al. (2017). Flood events were identified based on the ratio between quick flow and base flow (calculation based on the methodology proposed by Chapman, 1991). The correspondence of flood events occurring both in the tile drain network and in the main river was verified. Then, single storm events were defined as events cumulating more than 1 mm precipitation. Flood events were then associated with rainfall events, and when multiple storm events were recorded during a single flood event, they were grouped into a single event. This procedure resulted in a dataset of 36 coupled storm-flood events occurring in both the river and the tile drain network between December 2017 and June 2019. The following analysis is based on these 36 flood events, although some supplementary individual events were recorded only in the Bonnée River or in the tile drain network.

2.6. Data analysis

For these 36 individual flood events, several characteristics were calculated including rainfall depth (mm), duration (h), mean and maximal intensity (mm·h\(^{-1}\)), flood event volume (m\(^3\)), total, rising and falling limb durations (h), mean and maximal discharge (m\(^3\)·s\(^{-1}\)), runoff coefficient (%), antecedent rainfall (rainfall depth cumulated over the previous 48 h, mm), mean and maximal concentration (mg·l\(^{-1}\)), sediment load (kg). Specific peak discharge was calculated by dividing the peak discharge by the catchment or tile drain network area. Sediment loads were obtained through the integration of the product of the water discharge and the sediment concentration time series.

Results were considered separately for winter (December to February), spring (March to May), summer (June to August) and autumn (September to November). A correlation matrix using Pearson correlation coefficients was used to analyze the statistical relationships between these variables.

The statistical analysis will be used to investigate (i) the tile drainage network dynamics and (ii) the global catchment dynamics.

3. Results and discussion

3.1. Rainfall and river catchment dynamics

During the monitoring period, two contrasted hydrological years (defined as years starting on September 1st) were recorded (Fig. 4).

The 2017–2018 hydrological year concentrated most of the rainfall and flood events. Moreover, during the monitoring period, most of the storm events occurred in winter and in spring (Table 1). From 1st January to 31th March the total rainfall amounted 254 mm, corresponding to 162% of the long-term average over the same period (157 mm).

These floods contributed 60% and 83% of the annual water fluxes in the river and the tile drain network, and 62% and 92% of the sediment fluxes. The flashiness of the water and sediment fluxes was previously demonstrated for headwater catchments (e.g. Navratil et al., 2011) and for tile drained areas (King et al., 2014; Grangeon et al., 2017), underlining the importance of conducting a high resolution monitoring in these systems.

Of note, heavy rainfall was observed in July 2018 after a dry period: only 7 mm was recorded in the previous 3 weeks. More than 42 mm was then recorded in less than 6 h. At a 10-minute time step, the maximum rainfall intensity reached 37 mm·h\(^{-1}\). This event generated a significant flood event, even leading to the flooding of a nearby village (located about 10 km away from the monitoring station), and corresponding to the highest peak discharges observed throughout the entire study period. This event suggested the occurrence of infiltration-excess overland flow in this lowland medium-sized catchment.

Furthermore, the river baseflow remained at a high level during 2017–2018, especially during winter (62% of the annual total water fluxes). This high contribution from baseflow underlines the high soil moisture levels observed during this period of long-lasting and continuous rainfall, also characterized by a low evapotranspiration. Accordingly, discharge from tile drains was high during this period. Moreover, eight flood events occurred during winter following low rainfall amounts (<10 mm), while flood events were never triggered by such a low rainfall amount during the other seasons. These observations, combined with the distribution of rainfall and the number of flood events recorded during seasons and over the monitoring period, indicated that this period was prone to saturation-excess runoff.

Although a quantitative study of the relative importance of infiltration- and saturation-excess could not be performed because of the lack of monitoring data across the entire catchment, this information,
combined with the calculation of the water balance (calculation provided in the supplementary material), demonstrated that both infiltration- and saturation-excess processes were involved in flood generation in the study area. This interpretation is in line with the findings of Saffarpour et al. (2016) and Grangeon et al. (2017), although the current research suggested their combined occurrence at a much larger scale. The occurrence of soil saturation in a drained catchment had important implications on the hydrological regime and on flow occurrence in the tile network. It will also affect sediment connectivity across the catchment by allowing runoff, and therefore sediment transport, to occur more regularly and to take place on parts of the hillslopes that would not be prone to infiltration-excess runoff.

### 3.2. Tile drainage network water dynamics

A constant low flow ($\approx 1 \times 10^{-3} \text{ m}^3\text{s}^{-1}$) was observed and measured over the entire monitoring period in the tile drainage network (Fig. 5a). It reflected the constant inflow of water from a local spring. As the corresponding discharge was constant and low, with the absence of suspended sediment in the flow, it was considered negligible in this study. In 2017–2018, tile drainage water discharge exhibited much higher values, the 25th decile of the discharge time series was 75%

### Table 1

Main hydrological characteristics of the monitored period. The flood event percentage is relative to the entire monitoring period (2017–2019).

| Hydrological year | Recorded rainfall (mm) – Percentage of the long term average (%) | Flood events recorded over the monitoring period (number-percentage) | Winter flood events during the hydrological year (number- percentage) | Spring flood events during the hydrological year (number-percentage) | Autumn and summer flood events during the hydrological year (number-percentage) |
|-------------------|-------------------------------------------------------------|---------------------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 2017–2018         | 716 mm – 112%                                             | 23-64%                                                      | 14-61%                                           | 7-30%                                           | 2-9%                                           |
| 2018–2019         | 408 mm – 64%                                              | 13-36%                                                      | 6-46%                                           | 3-23%                                           | 4-31%                                           |
higher in 2017–2018 (up to 0.03 m$^3$·s$^{-1}$) compared to discharges recorded in 2018–2019 (up to 0.02 m$^3$·s$^{-1}$). In 2017–2018 and, to a lesser extent, in 2018–2019, base flow was generated during winter and spring because of the high soil moisture content, which was progressively evacuated by tile drains, both during and between storm events. Moreover, flows from tile drains increased during rainfall events, in direct relation with rainfall depth. Consequently, most of the flood events (64%) were recorded during the 2017–2018 hydrological year. The quick response of the tile drainage flow to rainfall suggests the occurrence of a direct connection between the soil surface and the rest of the soil column, increasing water and sediment vertical connectivity across the soil profile. On the contrary, late in spring and during summer, transfers from the tile drainage system were ephemeral, with successive periods of low and high flows, corresponding to highly variable transfers and connectivity levels across the soil column.

Although a link was found between the discharged volume from tile drains and the rainfall depth (Fig. 6), two relationships had to be derived for winter, on the one hand, and the remaining seasons, on the other hand.

$R^2$ amounted to 0.62 and 0.42, respectively, and both regressions were significant at the 5% level. This result reflects the seasonal behavior of tile drain systems in the study area, despite the relatively high connectivity maintained throughout the entire year between soils and the drain network. This seasonal behavior reflects variations in the soil surface properties (e.g. soil crusting may prevent water infiltration into the soil, although in this study, infiltration capacity could not be measured), the sparse soil cover by vegetation as observed through qualitative soil surface observations (Fig. 7) and the low temperatures. Indeed, all of these factors directly influence the soil moisture content.

During rainfall events, a quick response of discharge was observed in the tile drainage network throughout the monitoring period (Fig. 5b, the quick flow is highlighted by the gray shaded area). A peak in the discharge time series was regularly measured, and overlaid on the rising limb of floods occurring during the soil saturation period. When focusing on the 36 identified flood events, 13 of them were characterized by the occurrence of two clearly different peaks, as illustrated in Fig. 5b, in both time and magnitude: a rapid and high-magnitude peak occurring at the beginning of the event overlaying on the global, longer and lower flood signal. Overall, 46% of the flood events displaying this double peak occurred during spring and 38% occurred in summer. As they were mainly recorded during spring and summer, this quick flow component is assumed to be controlled by flow occurring in soil macropores and shrink-swell cracks, which is in line with the results of previous studies (Kladivko et al., 1991; Øygarden and Jenssen, 1997). This hypothesis was also confirmed by field observations made during the current research (Fig. 7).

It is also possible that these peaks did occur in winter, although they were diluted by the higher magnitude of the winter flood events. Quantifying precisely the contribution of these two peaks over multiple hydrological conditions would provide an interesting perspective for future research.

In addition to these coupled river-tile drain flood events, 12 other events displaying this quick discharge component were measured in the tile drains only. All these events were observed during spring and summer. Our results demonstrated that, in addition to transfers triggered by soil saturation, preferential flow occurring through soils cracks and macropores may occur in the soil column. Various flow conditions and connectivity levels in the tile drains were therefore observed throughout the year. This result may have an important impact on the transfer time of water, sediment and the associated contaminants. Stone and Wilson (2006) previously measured this type of behavior in the US (Indiana) at the outlet of a single tile drain from a unique field, during two flood events. They demonstrated the important implications of these preferential flows, accounting for 11% to 51% of the total flood flow, on glyphosate transfers. Our study demonstrates, using high frequency and long time series that these preferential flows occur frequently. Moreover, their occurrence was confirmed at larger scales (multiple drained fields and flood events) and in another environmental context, suggesting that it may be a generalized behavior of tile drainage. On average, at the flood event scale, preferential flow (occurring through macropores and cracks), calculated as the volume measured during the fast peak relative to the total flood volume, supplied 10–15% of the water fluxes to the total tile drainage network. It was estimated by isolating this peak on the hydrograph and calculating the relative water volume, compared to the total flood event volume. Therefore, the substances applied to the fields may be transferred with these preferential flows to the river channel with limited effects of soil retention and degradation.

3.3. Tile drainage suspended sediment dynamics and transfers to the river

The dynamics of suspended sediment concentrations from tile drains were very episodic and they displayed a contrasted behavior over the two monitored years (Fig. 5a). At the beginning of the monitoring
period, when the baseflow remained at a high level, suspended sediment concentration displayed regular peaks, in response to rainfall events. This period of significant transport lasted for several months, until early March 2018. Then, the subsequent sediment concentration peaks occurred mainly when rainfall events were significant and after long periods without high flow periods in the tile drain network. During the 2017–2018 hydrological year, suspended sediment loads ranged from $6 \times 10^{-4}$ to 9 t km$^{-2}$ at the event scale for the tile drainage network (34 ha), while it was ranging from $1 \times 10^{-3}$ to $2 \times 10^{-1}$ t km$^{-2}$ during the 2018–2019 hydrological year. In addition to these fluxes, peak concentrations were also analyzed focusing on significant storm events, arbitrarily defined by suspended sediment concentrations higher than 250 mg l$^{-1}$. Thirty events with such high concentrations were recorded during the 2017–2018 hydrological year while during the 2018–2019 hydrological year, with only 56% of the 2017–2018 cumulative rainfall, less than 20 of these high concentration events were recorded. However, relatively high peaks of suspended sediment concentrations were also observed during this 2018–2019 monitoring year. Over these two years, respectively 71% and 57% of the events displaying high suspended sediment concentration peaks were measured during winter, corresponding to periods of high flows. Moreover, during storm events, fast sediment transport – calculated during the fast peak of the rising limb in a similar way as it was performed for water in Section 3.2 – represented, on average, 15% of the sediment load. The concentrations measured in the tile drain network were in agreement with those found in other studies conducted at a tile drain outlet located in an agricultural catchment in a comparable environment in France (Grangeon et al., 2017). The high concentrations, along with the significance of fast transport from tile drains, highlight the potential major impact of tile drain water and sediment fluxes from multiple tile drains throughout the year.

A large scattering was observed in the relationship between specific peak discharge and specific sediment load when considering the entire data set ($R^2 = 0.57$), which confirms results obtained by Chapman et al. (2005). Interestingly, this relationship was higher when tested separately for winter and for the other seasons (Fig. 9).

In similar lowland drained catchments with gentle slopes, tile drains are usually immersed during flood events. The studied catchment configuration provided an original framework to isolate and analyze water and sediment fluxes from multiple tile drains throughout the year and in contrasted hydrological conditions (baseflow and flood events).
However, due to this particular configuration, it was not possible to investigate in detail the interactions between river/ditches and tile drain flows, which are likely to occur in similar catchments. This could be usefully addressed in future investigations.

Moreover, the two studied years were either wet or dry. It offered contrasted conditions to study the tile drain dynamics, which should have provided data of the tile drain network functioning under “extreme” conditions. However, because only two monitoring years could be recorded, the effects of successive wet, mean or dry years could not be investigated. Therefore, monitoring tile-drained catchments over longer periods should provide valuable insights into tile drain dynamics, especially regarding the hypothesized processes of sediment storage and exhaustion. Medium to long-term water and sediment drainage monitoring is indeed extremely scarce in the literature (Esteves et al., 2019) and, to the best of our knowledge, do not exist in the case of tile drain.

The current study however used an original experimental set-up to measure water and sediment flow originating from tile drains, using high frequency monitoring. Such data sets, extremely scarce in the literature, provided insights into the hydrographs and sediment fluxes generated from multiple drained plots under contrasted monitoring conditions including both a wet and a dry year. Based on this unique monitoring, a conceptual diagram of tile drain functioning is proposed (Fig. 10).

4. Conclusions

Water and suspended sediment dynamics were characterized during two hydrological years in a drained agricultural lowland catchment. A specific drainage collection network allowed the detailed quantification of water and sediment fluxes originating from a 34-ha surface area of drained fields. The results showed the very dynamic behavior of the tile drainage system. At the event scale, suspended sediment loads from the tile drains were significant, ranging from $6 \times 10^{-4}$ to $9 \times 10^{-2}$ t km$^{-2}$. The occurrence of double transfer pathways in the tile drains, previously demonstrated in the literature although for individual plots, was confirmed in this study for multiple plots, suggesting that this process may be widely significant in tile-drained environments. Water and sediment fluxes occurring during the fast stages of tile drain flood events were calculated to be in the order of 15% of the total flood event fluxes. The data suggests that the succession of deposition and resuspension stages of sediment stored in the drainage network play a significant role in sediment dynamics in the tile drain system.

Although these results may reflect the behavior of an individual catchment, the original experimental set up allowed insights into the hydrographs and sedigraphs of multiple drained plots. In the future, the factors controlling the sediment storage originating from the cultivated topsoil layer to the tile drains during ephemeral flow conditions should be further quantified, for instance through the measurement of short-lived fallout radionuclides characterized by contrasting half-lives (e.g. $^{7}$Be, $^{210}$Pb) or alternative low-cost measurements (e.g. color, magnetic susceptibility). Furthermore, the impacts of these transfers and their dynamics on sediment and contaminant exports from agricultural drained catchments should be further quantified in these lowland environments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.105033.

References

Akay, O., Fox, G.A., 2007. Experimental investigation of direct connectivity between macropores and subsurface drains during infiltration. Soil Sci. Soc. Am. J. 71 (5), 1600-1606.

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci. Data 5, 180214.

Blann, K.L., Anderson, J.L., Sands, G.R., Vondracek, B., 2009. Effects of agricultural drainage on aquatic ecosystems: a review. Crit. Rev. Environ. Sci. Technol. 11, 909-1001.

Cerdan, O., Souchère, V., Lecomte, V., Couturier, A., Le Bissonnay, Y., 2002. Incorporating soil surface crusts processes in an expert-based runoff model: sealing and Transfer by Runoff and Erosion related to Agricultural Management. Catena 46, 189-226.

Chapman, T.G., 1991. Comment on “Evaluation of automated techniques for base flow and recession analyses”. Water Resour. Res. 27, 1483-1484.

Chapman, A.S., Foster, I.D.L., Lees, J.A., Hodgkinson, R.A., 2005. Sediment delivery from agricultural lands to rivers via subsurface drainage. Hydrolog. Process. 19, 2875-2897.

Collin, A.L., Pulley, S., Foster, I.D.L., Gellis, A., Porto, P., Horowitz, A.J., 2017. Sediment source fingerprinting as an aid to catchment management: a review of the current state of knowledge and a methodological decision-tree for end-users. J. Environ. Manage. 194 (1), 86-108.

Cooper, R.J., Krueger, T., Hiscock, K.M., Rawlins, B.G., 2015. High-temporal resolution fluvial sediment source fingerprinting with uncertainty: a Bayesian approach. Earth Surf. Proc. Land. 40, 78-95.

De Girolamo, A.M., Pappagallo, G., Lo, A., Porto, A., 2015. Temporal variability of suspended sediment transport and rating curves in a Mediterranean river basin: the Celone (SE Italy). Catena 126, 135-145.

De Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. Earth Sci. Rev. 71, 95-125.

Denzy, C., Brazier, R.E., Heathwaite, A.L., Hodgkinson, R., 2009. Pathways of runoff and sediment transfer in small agricultural catchments. Hydrolog. Process. 23, 1349-1358.

Delmas, M., Pak, I.T., Cerdan, O., Souchère, V., Le Bissonnay, Y., Couturier, A., Sorel, L., 2012. Erosion and sediment budget across scale: a case study in a catchment of the European loess belt. J. Hydrol. 420-421, 255-263.

Duver, C., Nord, G., Gratio, N., Navratil, O., Nadal-Romero, E., Mathys, N., Némery, J., Regués, D., Garcia-Ruiz, J.M., Gallari, F., Esteves, M., 2012. Towards prediction of suspended sediment yield from peak discharge in small erodible mountainous catchments (0.45-22 km$^2$) of France, Mexico and Spain. J. Hydrol. 454-455, 42-55.

Esteves, M., Legout, C., Navratil, O., Evrard, O., 2019. Medium term high frequency observation of discharges and suspended sediment in a Mediterranean mountainous catchment. J. Hydrol. 568, 562-574.

Evrard, O., Vandeele, K., Bielders, C., Weemael, B., 2008. Seasonal evolution of runoff generation on agricultural land in the Belgian loess belt and implications for muddy flood triggering. Earth Surf. Proc. Land. 33, 1285-1301.

Evrard, O., Nord, G., Cerdan, O., Souchère, V., Le Bissonnay, Y., Bonté, P., 2010. Modelling the impact of land use change and rainfall seasonality on sediment export...
from an agricultural catchment of the northwestern European loess belt. Agric. Ecosyst. Environ. 138, 83–94.

Fiener, P., Wilken, P., Auerswald, K., 2019. Filling the gap between plot and landscape scale – eight years of soil erosion monitoring in 14 adjacent watersheds under soil conservation at Schevern, Southern Germany. Adv. Geosci. 48, 31–48.

Foucher, A., Lacey, J.P., Salvador-Blanes, S., Evrard, O., Le Gall, M., Lefevre, I., Cerdan, O., Rajkumar, V., Denuit, M., 2015. Quantifying the dominant sources of sediment in a drained lowland agricultural catchment: the application of a thorian-based particle size correction in sediment fingerprinting. Geomorphology 250, 271–281.

Frey, S.K., Hwang, H.T., Park, Y.J., Hussain, S.I., Gottschall, N., Edwards, M., Lapen, D.R., 2016. Dual permeability modelling of tile drain management influences on hydrologic and nutrient transport characteristics in macroporous soil. J. Hydrol. 525, 392–406.

Grangon, T., Maniere, L., Foucher, A., Vandromme, R., Cerdan, O., Evrard, O., Pene-Galland, I., Salvador-Blanes, S., 2017. Hydro-sedimentary dynamics of a drained agricultural catchment: a nested monitoring approach. Vadose Zone J. 16 (12) https://doi.org/10.2136/vzj2017.05.0113.

Haddadi, A., Ryder, D.S., Evrard, O., Olley, J., 2013. Sediment fingerprinting in fluvial systems: a review of tracers, sediment sources and mixing models. Int. J. Sedim. Res. 28, 560–578.

Hansen, A.L., Refsgaard, J.C., Christensen, B.B.R., Jensen, K.H., 2013. Importance of including small-scale tile drain discharge in the calibration of a coupled groundwater-surface water catchment model. Water Resour. Res. 49, 585–603.

Kemp, P., Dars, D., Croll, A., Naden, P., Jones, I., 2011. The impact of fine sediment on riverine fish. Hydrol. Process. 25, 1800–1821.

King, K.W., Fausey, N.R., Williams, M.R., 2014. Effects of subsurface drainage on tile drainage and groundwater flow route contributions to surface water contamination: from field-scale concentration patterns in groundwater to catchment-scale surface water quality. Environ. Pollut. 158, 3571–3579.

Russell, M.A., Walling, D.E., Hodgkinson, R.A., 2001. Suspended sediment sources in two small lowland agricultural catchments in the UK. J. Hydrol. 252, 1–24.

Saffarpour, S., Li, H., Sivapalan, M., Tian, F., Liu, D., 2010. Water and nutrient balances in a large tile-drained agricultural catchment of the northwestern European loess belt. Agric. Ecosyst. Environ. 138, 392–406. https://doi.org/10.1016/j.agee.2010.04.020.

Tournebize, J., Henine, H., Chaumont, C., 2020. Gérer les eaux de drainage agricole: du génie hydraulique au génie écologique ». Sciences Eaux & Territoires 32, 32–40. https://doi.org/10.14758/SET-REVUE.2020.2.06.

Uilen, B., Gunborg, A., Kreuger, J., Svansback, A., Etana, A., 2012. Particulate-facilitated leaching of glyphosate and phosphorus from a marine clay soil via tile drain. Acta Agriculturae Scandinavica. https://doi.org/10.1080/09647055.2012.697572.

Van Den Bogaert, R., Labile, J., Cornu, S., 2013. Aggregation and dispersion behavior in subsurface drained clayey soils. J. Environ. Qual. 30, 182–190. https://doi.org/10.2136/jeq2012.03.0166.

van der Ploeg, A., 1993. Modelled leaching of nitrate and phosphorus from an agricultural field with different subsurface drainage methods on water outflow components in a clayey agricultural field in boreal conditions. Agric. Water Manag. 121, 135–148.

Walling, D.E., Collins, A.L., Hodgkinson, R.A., 2001. Suspension of sediment in surface runoff and drainflow from clayey soils. J. Environ. Qual. 30, 143–150. https://doi.org/10.2136/jeq2001.03.0166.

Walling, D.E., Russell, M.A., Hodgkinson, R.A., Zhang, Y., 2002. Establishing sediment budgets for two small lowland agricultural catchments in the UK. Catena 37, 323–353.

Walling, D.E., Collins, A.L., 2008. The catchment sediment budget as a management tool. Environ. Sci. Policy 11, 136–143.

Walling, D.E., Hodgkinson, R.A., 2001. Suspended sediment sources in two small lowland agricultural catchments in the UK. J. Hydrol. 252, 1–24.