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Creation of an observatory of sediment transfers in Lower Normandy hydrosystems (western France) in the context of the European Water Framework Directive application

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Mots clés : observatoire, transferts sédimentaires, érosion des sols, connectivité, érosion de berge.

Version française abrégée

Création d'un observatoire des transferts sédimentaires dans les hydrosystèmes bas-normands (France de l'Ouest) dans le contexte d'application de la Directive Cadre Européenne sur l'eau. La quantification et la caractérisation des transferts hydrosédimentaires constituent aujourd'hui des enjeux majeurs, non seulement en termes de connaissance du fonctionnement des hydrosystèmes mais également pour la gestion des milieux et de leurs ressources naturelles. En effet, les conséquences associées à ces transferts peuvent être catastrophiques pour les écosystèmes continentaux et aquatiques, la biodiversité ainsi que les populations lorsqu'ils s'accompagnent de transfert de polluants, d'inondation ou de pollution, autant de problématiques cruciales pour la préservation et la restauration de la ressource en eau et sols qui sont aujourd'hui une des priorités environnementales des pouvoirs publics (Loi sur l'Eau, Directive Cadre sur l'Eau). De nombreuses études scientifiques ont été menées au cours des années passées sur la quantification et l'analyse des dynamiques des transferts sédimentaires. Cependant, les hydrosystèmes de faible énergie ($< 15 \text{ W/m}^2$), caractéristiques d'un large quart NW de la France, apparaissent peu documentés. De plus, ces études ne s'interrogent que rarement sur l'origine et les modes de transfert des sédiments dans le bassin-versant. En effet, réalisées en règle générale sur les principaux systèmes fluviaux ou aux exutoires de petits bassins versants de quelques km^2 , ces mesures permettent difficilement l'analyse des dynamiques et les transferts d'échelles internes au bassin-versant. Il s'agit pour-tant de problématiques fondamentales qui doivent permettre d'orienter les actions de gestion dans les bassins versants sur les zones les plus problématiques. C'est pourquoi, pour aller au-delà du fonctionnement « en boîte noire » du bassin-versant et comprendre le rôle de l'emboîtement des échelles sur les dynamiques spatiales et temporelles des transferts sédimentaires, le laboratoire GEOPHEN a fait le choix de mettre en place un observatoire des transferts sédimentaires dans les hydrosystèmes bas-normands qui s'appuie sur le suivi du bassin-versant de la Seulles (450 km^2), représentatif des hydrosystèmes observés en Basse-Normandie. L'objectif de cet

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observatoire est d'identifier, à l'aide de bilans quantitatifs et qualitatifs, les différentes sources sédimentaires dans le bassin-versant ainsi que les dynamiques temporelles de ces transferts au cours de l'année hydrologique. Ainsi, en vue de l'application de la Directive Cadre sur l'Eau, cet observatoire permettra de focaliser les actions de gestion des transferts sédimentaires sur les points les plus problématiques de ces hydrosystèmes. Cet article présente les différentes méthodes mises en place pour identifier et quantifier l'origine des sédiments au sein du bassin-versant de la Seulles. Deux sources sédimentaires sont ainsi envisagées : les processus de ruissellement érosif dans les parcelles agricoles et la remobilisation de stocks hérités par érosion de berge. La mise en place d'un réseau de mesure haute fréquence des transferts de sédiments est utilisée comme outil de contrôle par l'aval de la contribution des sources sédimentaires préalablement quantifiées.

1 Introduction

The quantification and characterisation of hydrological and sedimentary transfers are now major challenges, not only in terms of knowledge of hydrosystems, but also for the management of the environment and its natural resources. Indeed, the consequences associated with these transfers can be catastrophic for land ecosystems and aquatic biodiversity as well as for people, when they are accompanied by transfers of pollutants, flooding or pollution. There are so many critical issues to preserve and restore water resources and soils that they are now one of the government's environmental priorities (Law on Water; Water Framework Directive, WFD).

Numerous scientific studies have been conducted over the years on the quantification and analysis of the dynamics of sediment transfers in France. A census, carried out on them at the European level (Vanmaercke et al., 2011), clearly shows that many monitoring studies were conducted in the southern part of the country, subject to transfers and specifically high levels of erosion rates (Descroix, 1994; Pont et al., 2002; Scäfer et al., 2002; Esteves & Ludwig, 2003; Rollet, 2007). As for low-energy water systems (typically $< 15 \text{ W/m}^2$), a typical feature in a large quarter of NW France, they seem to have been much less documented, although, in Europe, other references exist in similar contexts: in Belgium (Verstraeten & Poesen, 2003), Britain (McManus & Duck, 1996; Heywood & Walling, 2003), Germany (Asselman, 2000) and Spain (Rodriguez Blanco et al., 2010). Nevertheless, these studies have rarely wondered about the origin and modes of sediment transfers in the catchment. Indeed, these measurements have, as a rule, been performed on the largest river systems such as the Loire, the Seine and its tributaries (Meybeck et al., 2003) or on the outlets of small, several square kilometre large catchment areas (Sogon et al., 1999; Lefrançois, 2007); so, these measures make it difficult to analyse the dynamics and the scale of transfers internal to the catchment. Yet, these are fundamental issues that ought to help guide management actions in the catchments of the most problematic areas.

Therefore, to go beyond the "black box" study of the way the catchment works and to understand the role of interlocking scales on the spatial and temporal dynamics of sediment transfers, the GEOPHEN laboratory has chosen to set up an observatory of sediment transfers in Lower Normandy hydrosystems. The purpose of this observatory is to identify (using quantitative and qualitative reports) the different sediment sources in the catchment and the temporal dynamics of such transfers during the hydrological year. Two sedimentary sources have been considered: the processes of erosive runoff in agricultural plots and the remobilisation of stocks inherited by way of bank erosion. The observatory is based on the priority monitoring of the Seulles catchment (Calvados). This catchment, located west of the Caen conurbation, has a 430-km² area; it is situated on the western end of the Armorican Range, in its upstream part, and on the sedimentary plateaus of the Caen plain, in its downstream part. Its location at the meeting point between these two morphological-structural units has resulted in the area boasting great variety

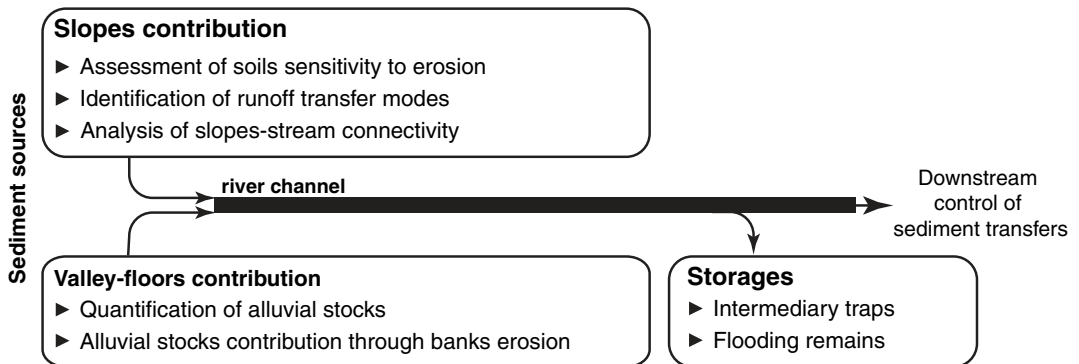


Fig. 1. Approaches chosen to quantify and identify the origin of sediments within the Seulles catchment.

in geomorphology, soil and landscape, which makes the Seulles catchment representative of hydrosystems observed in Lower Normandy.

The objective here is to present the Lower Normandy hydrosystems observatory, set up on the Seulles catchment, and to highlight the different approaches chosen to quantify and identify the origin of sediments within the Seulles catchment (Fig. 1). The first part will introduce the methods implemented on the slopes regarding the issues of sensitivity to soil erosion and runoff transfer arrangements between slopes and stream. Second, we will focus more on methods to assess the contribution of alluvial storages in valley-floors to the overall sediment budgets of the Seulles catchment. Finally, the last part will describe the network of high-frequency sedimentary transfer measurements in place in the catchment. This is to be used as a downstream control-tool about the contribution of previously quantified sediment sources.

2 Slope contribution

Sediment production due to soil erosion on the slopes is one of the first potential sources of a stream sediment load (Delahaye, 1996, 2002). Analysing sediment production requires first the potential soil erosion to be considered on the scale of the agricultural field. This evaluation was conducted by modelling the soil erosion uncertainty in the Calvados district between 2006 and 2007 (Le Gouée & Delahaye, 2008). Based on the SCALE model (Le Gouée et al., 2010), this model combines and prioritises a set of parameters relating to cultural practices, as well as to the intrinsic soil characteristics and climatic context, so as to define six classes of soil sensitivity to erosion, comprised between 0 (no sensitivity to erosion) and 5 (very high susceptibility to erosion; Fig. 2). All the parameters included in the model are mapped on the scale of the PAC island (i.e., one parcel or group of parcels), which warrants a fine mapping of soil sensitivity to erosion.

It is difficult, however, to establish a priori links of cause and effect between the marked sensitivity of soils to erosion, as seen across the agricultural parcel on one hand, and sediment transfers exported from the catchment on the other. Indeed, land use and catchment landscape structure will combine to create a complex network of artificial drainage that will profoundly change the runoff path on slopes, and connect to the main channel surfaces, sometimes a far distance from the stream (Carlier & De Marsily, 2004; Bocher, 2005). Moreover, even if sediment transfers are observed at the plot level, the arrangement in space of the network of hedges or sloping banks might disconnect a more or less extensive part of the catchment from the river (Mérot et al., 1999). The entity "catchment" should, therefore, be considered as a complex system where the processes observed at the plot scale does not necessarily determine the overall

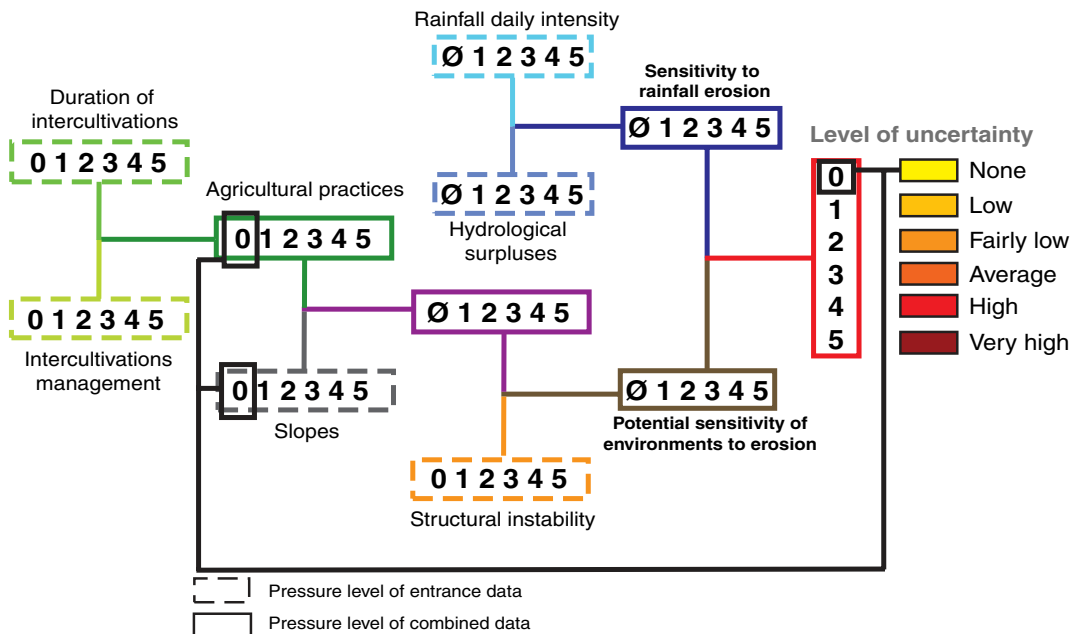


Fig. 2. Organisation of the SCALES model (Le Gouée et al., 2010).

catchment response (Delahaye, 2002; Cerdan et al., 2004; Slaymaker, 2006; Delahaye, 2008; Delahaye et al., 2010). Therefore, beyond a level of surface static sensitivity, it is necessary, in parallel, to develop a dynamic approach to the erosive system, highlighting the impact of spatial interactions between different components of the environment (plots, hedge-networks, ditches and roads) on the runoff dynamics at the surface of slopes (Viel, 2006; Viel et al., 2009).

Hydrological linkages that determine runoff on slopes may be of different natures. However, they are constrained by a constant: the organisation of slope systems that guides the setting in motion of water at the ground surface. Runoff dynamics is then influenced by two factors: land use and the landscape structure in the catchment consisting of all linear features such as hedges, embankments, ditches or road network, whose impact on the runoff flow on slopes is to be evaluated. This assessment can be broken down from a methodological point of view into three successive stages. One first step is to conduct an environmental diagnosis (Fig. 3). The objective is to develop an inventory of hydrological linkages on slopes by highlighting the impact of landscape structure on the flow of water down the slopes. Four types of impacts can thus be distinguished: (i) Surfaces (they play a role in runoff production: land use and road network); (ii) Linear features (they promote connection between the runoff and the stream: the network of ditches and roads); (iii) Field entries (they provide the connection between agricultural parcels and networks); (iv) Hedges (they deviate or store water runoff on the slopes).

However, each of the hydrologic effects of land use and catchment landscape structures will combine their impacts. Our discussion, therefore, turned to an analysis of the connectivity of surface runoff between slopes and the stream. Analysis of the hydrological connectivity has been developing greatly since the early 2000s (Ali & Roy, 2009). The enthusiasm felt for this concept is mainly due to the multi-scalar approach of catchment functioning that the concept makes possible. Indeed, by linking interdependent processes such as soil erosion on hillsides and sediment transport by a river – taking place at different spatial scales, namely the agricultural parcel and the catchment – it allows parcels or groups of parcels that potentially contribute to the stream sediment load to be located. Then, parameters responsible for a share of sediment production and parameters for (sometimes complex) runoff circulation on slopes are both taken into ac-

Drawing up an environmental diagnosis

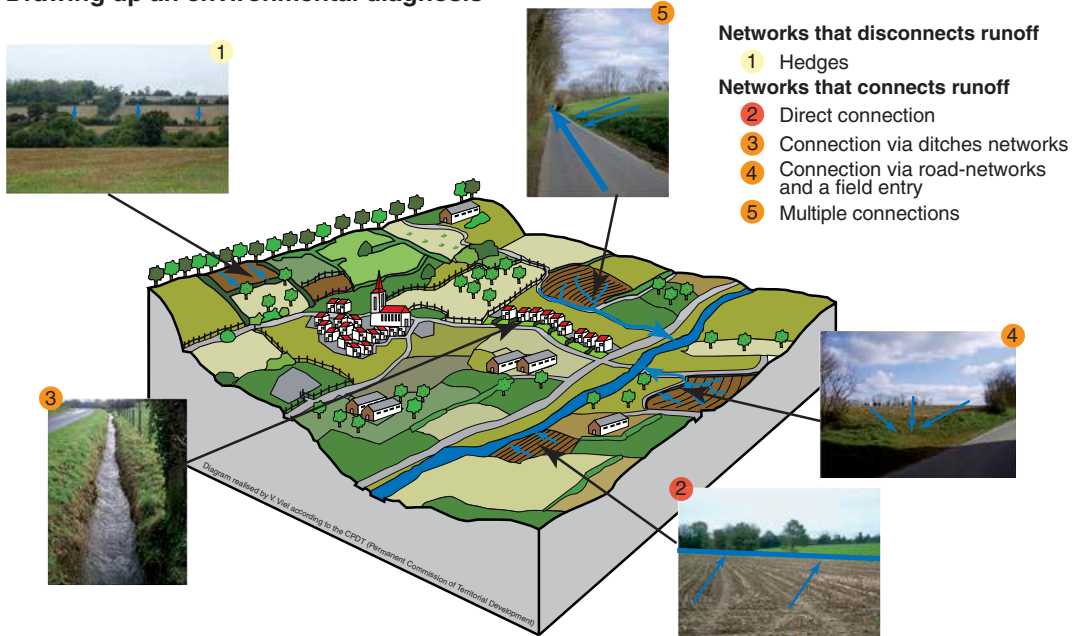


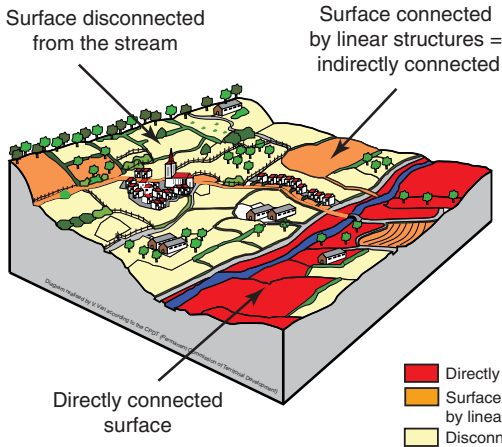
Fig. 3. Modes of surface runoffs transfers.

count. Thus, by providing a tool to measure the impact of the structure of land use and linear developments on the overall functioning of a catchment, the concept of hydrological connectivity can contribute to the debate on the issues of measurement scale of transfers within catchment areas (plot, slope and catchment). In this respect, the analysis of hydrologic connectivity is now considered essential for understanding catchment behaviour (Ali & Roy, 2009).

The concept of hydrological connectivity has been used to accurately determine the surfaces connected to the rivers that are the only ones able to contribute to the latter's sediment load. We shall, therefore, analyse hydrologic connectivity, to identify the areas potentially connected to streams, given the topography, land use and the organisation of the catchment landscape structure. To measure hydrological connectivity, a typology of the catchment hydrologic connectivity has been drawn up and mapped (Fig. 4A). Three categories can be distinguished, which split the catchment entity into a set of islets, which are, or not, connected to the catchment. This leads to distinguish: (i) Surfaces "directly connected" to the stream. This is the simplest connection, where no obstacle modifies the purely topographic dynamics of runoff flow. These parcels or groups of plots are most often located along the river; (ii) "Indirectly connected surfaces". In this case, the linear developments are responsible for connecting the runoff to the river; (iii) The remaining surfaces of the catchment are then considered as being "disconnected" from the river.

Finally, the third stage integrates the spatial organisation impact of land use on runoff within each islet. The study then focuses on the layout of grasslands (which provide re-infiltration opportunities) compared to cultivated areas (Fig. 4B). The grasslands found in the islets actually do not all have the same stabilising effect on surface runoff. Indeed, more than the percentage of grassland in the islets, their organisation and spatial structure will define the latter's ability to re-infiltrate some or all the runoff. This mapping is used to evaluate the connectivity potential of slopes vis-à-vis the river. However, beyond this "static" (Lexarta-Artza & Wainwright, 2009) or "structural" (Bracken & Corke, 2007) approach of hydrological connectivity, it is necessary to have a more functional approach of the identified contributing areas. Therefore, the final stage of the

A Cartography of hydrological connectivity



B Localisation of the surfaces contributing to the sediment bed load

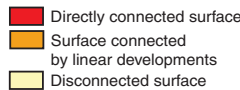
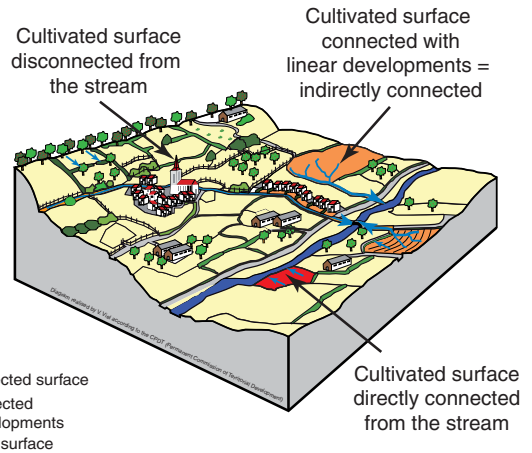


Fig. 4. Methodological approach to analyse hydrological connectivity between slopes and stream (Viel, 2012).

research seeks to quantify the sediment contribution of each of the connected surfaces, since their contribution may vary significantly from one surface to another. Samples – taken during the major hydrological episodes at the previously mapped outlets of connection islets – allows the assessment, at the scale of the small representative catchments that have been monitored, of the slope contribution to the catchment overall sediment budgets.

3 Valley-floor contribution

Valley floor contribution, coming from the remobilisation of stocks inherited by the river lateral adjustment, is a second possible origin of the sediment load carried by the Seules River. Some studies have shown, actually, that the contribution from that source was not negligible and made up the majority, by far, of the sediment budget of some catchments (Lefrançois, 2007).

Valley-floor contribution raises a first issue: the existence of a sediment stock potentially mobilised by the river. It is therefore necessary to quantify and reconstruct the alluvial stocks stratigraphy. From a methodological point of view, such quantification was divided into different stages. First, valley-floor spatial extension were delineated from a DTM (Digital Terrain Model; Germaine et al., 2007). The valley-floor morphology, the vertical alignment and the drainage organisation within the catchment allowed the delineation of 38 sections wherein the sediment is considered as homogeneous. Within each of these sections, a cross-section was made to estimate the change in sediment thickness across the valley (Fig. 5). A total of 202 boreholes have been planned, drilled with hand-auger, Russian probe and percussion-corer. The geometry of the valley-floor, combined with the thickness of the alluvial fills, then made it possible to estimate the volume of each section. 2 to 3 m high silt banks are commonly observed in the Seules River transfer area, which suggests a priori that the alluvial stocks likely to be mobilised are substantial (Lespez et al., 2005, 2008; Viel et al., 2011).

Since the alluvial stock is extensive, it was necessary to focus on its contribution to sediment flows exported from the catchment. From a methodological point of view, different methods designed to quantify the banks retreat rates exist. Some of them are based on picture interpretation, whether aerial photographs or high-resolution satellite pictures. Others combine high-resolution



Fig. 5. Examples of the Seules River (Le Heuzé) that have been studied for monitoring bank retreat processes (photographs by D. Delahaye, 2010).

measurements tools such as monitoring by DGPS for example. However, these methods could not be used here. Indeed, on account of the reduced speed of banks retreat, in most cases the range of measurements lies within these methods margin of error, especially when using old aerial photographs. This problem is accentuated by the fact that the linear banks are repeatedly obscured by riparian vegetation. It is, therefore, difficult in both cases to determine the limits of banks with certainty and sufficient accuracy. Hence, it was necessary to use in-situ equipment in various sites.

It was obviously not possible to equip and monitor the entire Seules linear banks. Thus, to identify the sites that are representative of the different processes and the latter's different levels of intensity, a typology of bank erosion on the basis of their observed erosion was carried out on all the banks of the Seules River and its tributaries. This typology – based on a combination of seven factors characterising successively the erosion degree, its nature, the nature of the bed, the nature of riparian vegetation, the afforestation rate, the rate of revegetation and degree of meandering – allowed us, by combining all factors, to identify 100 m to 200 m long homogeneous sections (Douvinet, 2003). A set of eight reference sites, defined as undergoing high and medium erosion, were then selected. These are located according to their position within the river system: 4 on the main channel and four others on tributaries whose outlet sediment flows were measured. The linear banks integrated in the low erosion category have so far not been equipped, as erosion there is considered negligible. The concave banks of each of the selected sites have been equipped with 30 and 40 cm long erosion stems and with 162 cm long nails. The breakdown is as follows: a vertical profile was performed every 2 m of linear stream. The erosion stems and the nails were then positioned perpendicularly to the bank, every 20 cm down to the foot of the bank. The nails were driven to flush while erosion stems emerge from the bank at a height of about 5 cm.

This method of quantification is a first step in evaluating the contribution of alluvial storage in the transfer of current sediments. Other methods to refine the quantification or improve the time resolution of banks erosion, however, will be considered later. Thus, the site showing largest retreat rates was subject to a land laser scanning in June 2011. A second scan campaign will be conducted in late winter 2012, to quantify bank retreat more precisely and discuss the results obtained by the erosion stems method. The establishment of photovoltaic rods can also be considered to measure retreats at higher frequencies. The results obtained at the scale of the reference site are then extrapolated to the catchment scale and are discussed by comparison with the sediment transfer values measured at high frequency by on-site network monitoring.

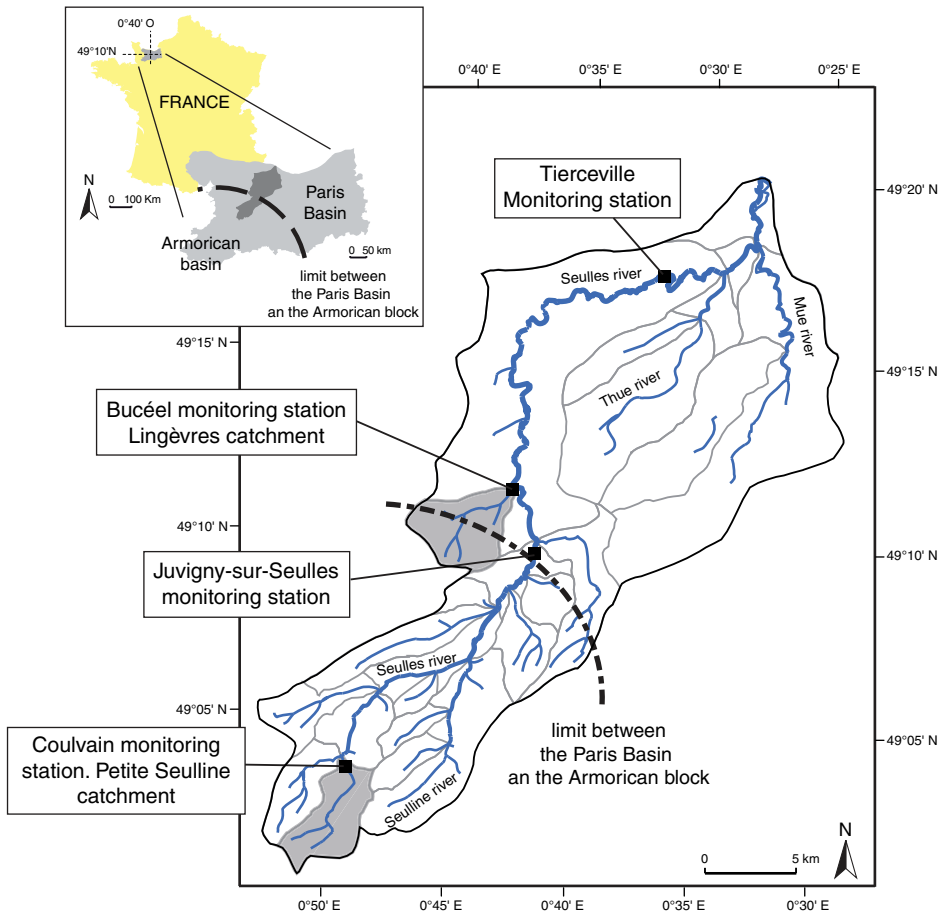


Fig. 6. Organisation of the network monitoring in the Seules catchment.

4 Control of sediment transfers conducted downstream

Monitoring and analysis of sediment transfers carried out on the Seules River was the focus of our thinking. Its main objective was to obtain fine measurements of sediment volumes exported from the catchment area at different spatial scales and in different hydrological contexts. This will make it possible to discuss the results obtained in the course of the debate on the sediments origin and to describe the annual and seasonal dynamics of sediment transfers. However, because of the size and heterogeneity of the catchment, it is necessary to build a network of different monitoring stations for measuring sediment flows in different contexts and at different scales.

Organisation of the monitoring network in the catchment. To measure sediment flows within the Seules catchment, a network of four monitoring stations was established (Fig. 6). The positioning of each measuring station in the catchment follows two complementary logics. Two stations allow us to measure sediment transfers across the basin. The first one is situated downstream (Tierceville) and measures sediment flows on a global scale. A second one (Juvigny-sur-Seules) is located at the interface between the Caledonian massif and the sedimentary basin. This allows, on one hand, to quantify the volumes of sediment exported from the Caledonian massif and, on the other, to measure the internal sediment production in the Paris Basin by reckoning



Fig. 7. Monitoring station placed at the outlet of the Lingèvres catchment.

the budgets between the two stations. To measure the effects of scale, the monitoring network is supplemented by two other stations located at the outlet of the representative catchments (15 km²). This allows the diversity of hydrological environments to be taken into account. One first station is located upstream, on the Caledonian massif, in hedgerow context (Petite Seulline), while a second one is set up at the outlet of a basin in a contact position (Lingèvres).

Metrology of sediment transfers. There are two main methods for estimating sediment flows in a catchment. The first is to directly measure the concentration of suspended solids (SS) from samples taken manually or using an automatic sampler, and at intervals in time set in advance by the user. The measurement of concentration, associated with flow permits the quantification of sediment volumes exported from a catchment. However, given the high variability of sediment transfers, particularly in times of flooding (Gao, 2008), it is necessary to take samples at high frequency, which is costly both in time and manpower, both in the field and in laboratory. This approach is, therefore, hardly feasible on an annual or multiannual scale, given the volume of samples that would need processing in the laboratory in a very short time. Therefore, it was chosen to quantify sediment transfers by monitoring turbidity. The turbidity measurement, developed in the 1990s (Jansson, 1992) and measured in Nephelometric Turbidity Unit (NTU) is an optical property that allows the quantification of the decrease in the diffusion intensity of light between an incoming beam and a photoreceptor. Thus, by making optical measurements instead of sampling, we avoid problems of sample storage and laboratory processing, which makes it possible to measure sedimentary flows at a high frequency, over long periods, and to multiply the measurement points within a catchment. However, this method requires each monitoring station to first go through a calibration phase between the current concentration of suspended solids – estimated from samples taken in the rivers – and turbidity. It, therefore, does not exempt researchers from carrying out frequent prior sampling, especially during floods. These turbidity measurements are performed using an MS5 (OTT) multiparameter probe rigged with a turbidity sensor whose measurements range covers the entire range of observed turbidity in the Seullles catchment (Fig. 7).

5 Conclusions

By mobilising all the methods available for analysing water resources (quantity, quality, excess, shortage) and by conducting sediment budgets and varying spatial scales, the establishment of an observatory of sediment transfers makes up an experimental site that is unique in a broad quarter of NW France at that scale. It can provide basic knowledge about the current processes active in these hydrosystems, that have been poorly documented so far, though these elements are fundamental ones if we are to return to the rivers' best ecological status, as requested by the WFD. A better understanding of sediment processes presiding over sediment transfers in these water systems makes it possible to guide actions in terms of river management. Similarly, by establishing an "original" state of the catchment, the observatory will then measure the effects of managers' actions. From a prospective point of view, it will also enable us to assess the impact of changes in one or more hydrosystem component(s) on the volume of sediments transported by rivers, as part of a changing climate.

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