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# RIVER DREDGING, CHANNEL DYNAMICS AND BEDLOAD TRANSPORT IN AN INCISED MEANDERING RIVER (THE RIVER SEMOIS, BELGIUM)

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## ABSTRACT

Dredging in the rivers of the Ardenne is generally carried out on a smaller scale to that described in the literature and is not conducted for commercial purposes. Extractions within the river channel are made in order to prevent flooding; hence the quantity of gravel extracted is limited. This study aims to evaluate the impact of dredging and the resilience of the riverbed in the Semois. This river is found in the south of the Ardenne region and is characterized by large incised meanders, a narrow floodplain, few pebble bars, numerous bedrock outcrops and a limited stock of sediment. The bed is particularly flat and shallow and the bankfull discharge ($130\,m^3\,s^{-1}$) is frequently attained (0.9 yr). Pebble tracers allowed the critical parameters (discharge, Shields criterion, and stream power), the diameter of mobilized sediment and the distance of sediment transport to be determined. A major dredging campaign resulted in the formation of a channel nearly 1 km long and 2 m deep which functioned as a sediment trap. Topographical cross-sections made before and after the dredging campaign and again 4 yr later allowed bedload discharge to be estimated ($1.1\,t\,km^{-1}\,yr^{-1}$). In order to examine the efficiency of the sediment trap, the sediment transport equations of Meyer-Peter and Müller, Schoklitsch, Bagnold and Martin were applied. With the exception of Bagnold's equation (1980), the observed transport values and those calculated theoretically are relatively close. Between October 1997 and June 2001, 5010 t were caught in the sediment trap. For the same period the equations calculate values between 6147 and 10 571 t. The overestimation from the theoretical calculations may result from a lack of sediment supply due to the characteristics of the basin and the frequency and magnitude of flood events during the study period. From the magnitude of the sediment transport rate, a return to the initial state of the riverbed (before dredging) may be expected after approximately 10 yr. Despite the scale of the dredging campaign for a river of this size, its results are limited in terms of flood prevention. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: incised meanders; dredging; bedload transport equations; sediment traps; critical discharge

## INTRODUCTION

From the 19th century, many rivers have been subject to gravel extraction, mainly for commercial purposes. Up to recent decades, this activity increased progressively and was particularly marked in regions experiencing urban and industrial growth and where there was generally a lack of other sources of sediment (Kondolf, 1994). The impacts of gravel extraction have been widely documented on the basis of case studies or literature reviews, especially in countries such as France (Peiry, 1989; Gautier, 1994; Peiry *et al.*, 1994; Landon and Piégay, 1994; Petit *et al.*, 1996; Bravard *et al.*, 1997; Gaillot and Piégay, 1999; Steiger *et al.*, 2000; Liébault and Piégay, 2001), Germany (Foeckler *et al.*, 1994; Reich, 1994), the United Kingdom (Sear and Archer, 1998), the United States (Bull and Scott, 1974; Collins and Dunne, 1989; Kondolf, 1997), Italy (Rinaldi and Simon, 1998; Surian, 1999; Surian and Rinaldi, 2003; Rinaldi, 2003) and Poland (Wyzga, 1993; Lach and Wyzga, 2002). Braided rivers and piedmont rivers are often preferred for gravel extraction. In any case the rivers chosen have, or originally had, an ample availability of sediment, even though the sediment supply to the river may not be adequate to compensate for the material extracted.

As well as contributing to the deterioration of the river environment, in-stream gravel mining may lead to channel incision, bed coarsening, and lateral instability of the channel (Kondolf, 1994, 1997). Incision of braided

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riverbeds may also contribute to the narrowing of the active channel as riparian vegetation cover grows, intruding on formerly active features (Kondolf *et al*., 2002; Liébault, 2003). An increase in gravel-bed mobility, which occurs if the pavement is disrupted by extraction, is another more subtle effect of in-stream gravel mining (Parker and Klingeman, 1982). Likewise, an increase in grain roughness may be observed once the coarse elements of the riverbed are exposed (Bravard and Peiry, 1993; Bravard *et al*., 1999). The removal of gravel bars by in-stream mining may disrupt the hydraulic balance of the section upstream, leading to the erosion of riffles (Pauley *et al*. (1989), cited by Kondolf (1997)). Bed incision increases the capacity of the channel and allows greater discharges to be evacuated without overflowing. This reduces, at least in the surrounding area, the frequency of floods (Bravard *et al*., 1999). In this way, extracting sediment may be looked on as a means of flood prevention (Bravard *et al*., 1999). Given its largely negative impacts, however, in-stream mining has been banned or heavily restricted in many European countries (Kondolf, 1997).

In the gravel-bed rivers of southern Belgium, sediment extraction (dredging) is primarily carried out in the low flow channel in order to limit the level of floods. This consists of skimming riffles and point bars. Sediment extraction has been restricted to a number of sites and carried out at specified times. The quantities of sediment taken from these rivers are hence limited and are far from the vast amounts taken from rivers in the countries discussed above. However, the sediment flux of the rivers of the Ardenne is also limited in comparison to that of other rivers in, for example, France, the Alps, Poland or Italy. Finally, the morphology of the Ardenne rivers and their floodplains differ drastically from those described in the literature.

The research for this paper forms part of a multidisciplinary study requested by the Walloon regional authorities, in order to develop a method of evaluating the impact of dredging on a river in the southern Ardenne. Its aim is to understand how the river functions in relation to the problem of dredging and to determine the time required for the reconstruction of bedforms. This entails evaluating the frequency of morphogenic floods, the quantities of sediment transported, the size of mobilized elements, the availability of sediment, the extent of lateral mobility and the stability of the low flow channel.

## THE STUDY AREA

The Semois is one of the main tributaries of the Meuse, draining most of the southern Ardenne region. This study was conducted on a 39 km section between Dohan and Laviot. Between these two villages the average slope is 0.104% and the low flow channel is 50–55 m wide. The area of the river basin at Laviot is approximately 1100 $km^2$ (the total area of the catchment at the Belgian border is 1235 $km^2$). In this section the Semois receives 8 modest-sized tributaries and one larger tributary (le Ruisseau des Aleines) which joins the river directly upstream from the study section (Figure 1).

On entering the Ardenne, the Semois cuts into phillytes and quartzo-phillytes from the Eodevonian period (Gedinian and Siegenian stages). The general orientation of its course (east–west) flows parallel to the regional schistosity of the metamorphic rocks. In accordance with Strahler's theory (1946), this brings about the formation of large incised meanders (Figure 1). Such a situation is exceptional in the Massif Ardennais where the other rivers generally flow perpendicular to the schistosity and therefore develop much smaller meanders (Alexandre, 1956; Pissart, 1960).

In the Ardenne, the Semois falls under the classification of an Osage-type underfit stream, as described by Dury (1964). Indeed, one of its morphological characteristics is the proximity of the valley sides. These do not allow the development of free meanders within the floodplain and lead to the presence of numerous bedrock outcrops which are perpendicular to the flow of the river. The exposed bedrock indicates that the pebble sheet is rather thin. In addition, bedrock plays an important part in the river dynamics as it maintains the longitudinal profile and prevents readjustments of the river's course.

However, despite the outcrops, the bed of the Semois generally appears to be very flat with limited development of riffle and pool sequences. Indeed, pockets surrounded by bedrock outcrops are filled with sediment. The low flow channel is hence particularly large and shallow (average width/depth ratio of 30.8) and the bankfull discharge is low and therefore more frequently attained by the Semois (0.9 years) than by the other better-known rivers of the northern Ardenne (1.2 to 1.5 years) (Petit and Pauquet, 1997). The thalwegs of the latter are characterized by

 

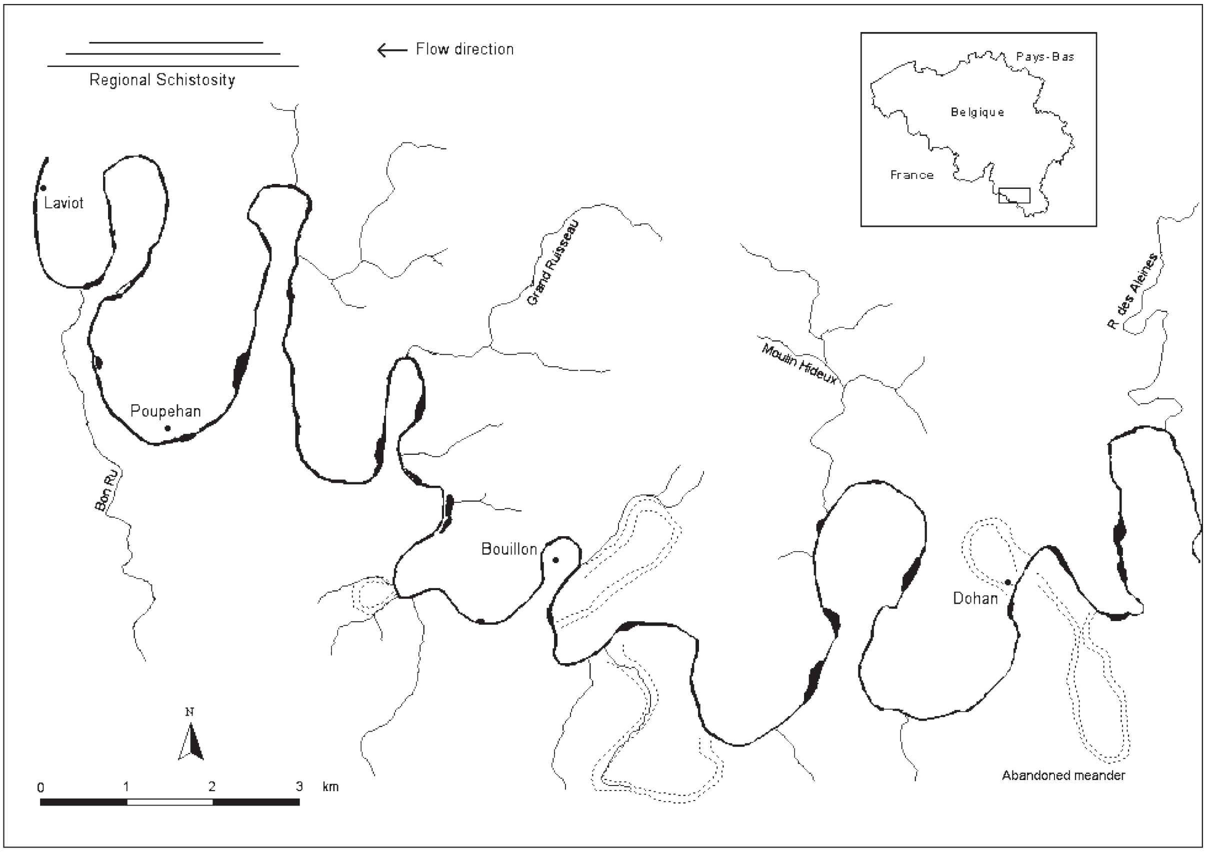


Figure 1. Locational map of the Semois River and its main tributaries between Dohan and Laviot

pronounced riffle and pool sequences and by large pebble bars that create marked differences in depth. Also, when comparing the Semois to the Ourthe (Table I) one remarks that despite lower shear stress ($\tau$), there is greater sediment transport in the Semois owing to the relatively low roughness of the bed. In the Ourthe, the roughness and therefore the bedform shear stress ($\tau''$) is greater and as a result sediment transport is more limited. In addition, the active band of sediment transport is larger in the Semois, which further increases the possibility of mobilization. With regard to the headwater streams, such as the Wamme and the Aisne, despite the fact that roughness is greater, steeper gradients and higher grain shear stress ($\tau'$) explain the greater sediment transport, as illustrated below.

The constrained nature of the course of the Semois was highlighted by studies on the formation of the Ardenne drainage network and its evolution during the Quaternary (Pissart, 1960). The study of ancient documents such as

Table I. Characteristics of several rivers of the Ardenne region

| | Catchment area ($km^2$) | $Q_b$ ($m^3 s^{-1}$) | Critical discharge ($m^3 s^{-1}$) | $D_{50}$ mobilized (mm) | Total roughness | $\tau'/\tau$ | $\omega$ for $Q_b$ ($W m^{-2}$) |
|---|---|---|---|---|---|---|---|
| Semois | 1235 | 130 | $>Q_b$ | 70 | 0.038–0.047 | 0.6–0.7 | 22.5 |
| Ourthe | 2660 | 300 | $<Q_b$ | 60 | 0.055 | 0.4–0.5 | 52 |
| Aisne | 190 | 24 | $=Q_b$ | 76 | 0.15 | 0.09–0.1 | 94 |
| Lienne | 146 | 16 | $<Q_b$ | 100 | — | — | 186 |
| Wamme | 80 | 17 | — | — | — | — | 109 |
| Warche | 118 | 15 | — | — | — | — | 74.5 |

 

Table II. Main characteristics of the Semois tributaries between Dohan and Laviot. Discharges and specific stream powers have been calculated during a flood with a recurrence interval of 25 yr

| | Catchment area ($km^2$) | Slope (%) | Width (m) | $D_{50}$ (mm) | $Q$ (07-01-01) ($m^3 s^{-1}$) | $\omega$ for the flood of 07-01-01 ($W m^{-2}$) |
|---|---|---|---|---|---|---|
| R. des Aleines | 46 | 0.6 | 11.5 | 85 | 15.5 | 73.9 |
| Moulin Hideux | 9.6 | 1.9 | 3.7 | 72 | 2.8 | 126.9 |
| Grand Ruisseau | 12.94 | 2.53 | 4.0 | — | 3.5 | 112 |
| Bon Ru | 10.98 | 1.65 | 6.0 | 106 | 5.1 | 73 |

topographical maps, postcards and aerial photographs shows that at least since the end of the 18th century the river's course has remained the same and lateral erosion has been low. Only a handful of islands have been removed or are in the process of being removed by infilling of one of their channels (Petit *et al.*, 2002).

The stretched shape of the incised meanders and the elongated form of the Semois basin limit the extension of its tributaries. Indeed, the entire area of their catchment covers only a few square kilometres. However, owing to their encasement, the tributaries of the Semois have marked slopes and a high specific stream power (Table II). They play an important role in the sedimentary dynamics of the main river as they supply the river with bedload and, in particular, with large-sized elements. Moreover, the confluences of the majority of the tributaries are characterized by the presence of an alluvial fan within the low flow channel of the Semois itself.

## METHODOLOGY

The sedimentary dynamics of the river were evaluated in order to assess the impacts of dredging campaigns and the resilience of the river system. The mobilization discharge, the size of mobilized elements and the distance travelled by the latter were calculated using bedload tracers. Sediment discharge was estimated by monitoring the refilling of a pit which had been hollowed out during an important dredging campaign in 1997 at Laviot. Topographical surveys were made on numerous occasions before and after the dredging. The value obtained was compared to the sediment discharge values calculated using different transport equations.

### *Bedload transport equations*

As Graf (1977) recommends, a number of formulae should be applied when evaluating bedload transport rates and the results, which may differ considerably, should be discussed. With this in mind, three methods based on different hydraulic parameters were applied for the purpose of this study.

The Meyer-Peter and Müller (1948) equation is one of the most commonly used bedload transport equations. It is based on grain shear stress ($\tau'$) compared to critical shear stress ($\tau_{cr}$) obtained using a Shields dimensionless criteria ($\theta_c$) of 0.047.

$$g_b = 0.253(\tau' - \tau_{cr})^{3/2} \tag{1}$$

The term $g_b$ is then multiplied by the specific density of wet sediment which gives a bed load transport rate per unit time and width (expressed in $kg\,m^{-1}\,s^{-1}$). Several studies have shown that this equation gives good results (Larras, 1977; Graf, 1977), however, the authors recognize that its application may lead to considerable overestimations. Indeed, this has been observed by Frecaut (1972) in his study on the Moselle.

The formula developed by Schoklitsch (1934) gives the sediment transport rate per unit time and unit width, according to the difference between the unit discharge and critical unit discharge:

$$g_s = 2500\,S^{3/2}(q - q_{cr}) \tag{2}$$

Here $q_{cr}$ is the critical unit discharge, which in Schoklitsch's initial formula may be obtained using a theoretical relation. The $q_{cr}$ used in this study is the observed critical discharge. This also applies for the Bagnold and

 

Table III. Bagnold formulas. In equations (4) and (5) reference variables had been defined by Williams (1970): $i_{br} = 0.1\ \mathrm{kg\,m^{-1}\,s^{-1}}$, $(\omega - \omega_0)_r = 0.5\ \mathrm{kg\,m^{-1}\,s^{-1}}$, $d_r = 0.1$ m and $D_r = 1.1\ 10^{-3}$

| | Formula | $\omega$ definition | Reference |
|---|---|---|---|
| (3) | $i_b/(\omega - \omega_0) = 1.6\ [(\omega - \omega_0)/\omega_0]^{1/2}\ (d/D)^{-2/3}$ | $\omega = \rho\ Q\ S/w$ ($\mathrm{kg\,m^{-1}\,s^{-1}}$) | Bagnold (1977) |
| (4) | $i_b = \gamma_s/(\gamma_s - \gamma)\ i_{br}\ [(\omega - \omega_0)/(\omega - \omega_0)r]^{3/2}\ (d/d_r)^{-2/3}\ (D/D_r)^{-1/2}$ | $\omega = \rho\ g\ Q\ S/w$ ($\mathrm{W\,m^{-2}}$) | Bagnold (1980) |
| (5) | $i_b = \gamma_s/(\gamma_s - \gamma)\ (\omega - \omega_0)^{3/2}(d/d_r)^{-2/3}\ (D/D_r)^{-1/2}$ | $\omega = \rho\ g\ Q\ S/w$ ($W m^{-2}$) | Bagnold (1986) |

Meyer-Peter equations, where the critical specific streampower ($\omega_0$) and the shear stress ($\tau_{cr}$) were calculated using the critical discharge observed on site with tracers (see below).

From data collected from natural rivers, Bagnold (1977) developed a relation linking sediment transport ($i_b$) to excess specific stream power, i.e. the difference between specific stream power ($\omega$) and critical specific stream power ($\omega_0$). Several versions of this equation were elaborated. The three versions (equations (3), (4) and (5)) shown in Table III were tested for this study. It should be noted that the term $g$ is included in the definition of specific stream power starting from equation (4).

Finally, from the data of Gomez and Church (1989), Martin (2003) proposed a simple correlation between sediment transport and specific stream power. This type of formula is regularly used, especially for studies of landscape evolution considering sediment transport at sub-grid scales (e.g. Tucker and Slingerland (1994) in Martin (2003)). It is not assumed to be as precise as other relations. It may be written as:

$$i_b = 0.0505\omega^{0.89} \tag{6}$$

where $\omega$ is expressed in kg $\mathrm{m^{-1}\,s^{-1}}$.

Martin (2003) recognized, however, that this formula only gives crude estimations for case studies with well-known hydraulic and sedimentary parameters.

*Sediment trap*

In order to protect the village of Laviot from flooding by the Semois, significant dredging of the riverbed was carried out in 1997 on a linear stretch of over 800 m. Precise topographical surveys were made before and just after dredging, and again in June 2001 and August 2002. Numerical models of the terrain were developed, based on a series of 18 transverse cross-sections spaced at 50-m intervals (except for cross-section 8 and A which were only 8 m apart) (Figure 2). The precision of the model depends on the size of the elements that make up the bed. When comparing the heights measured during different topographical surveys in the upper Ourthe ($D_{50} = 7$ cm), it has been shown that only differences in height greater than 5 cm should be considered (Jonet *et al*., 2001).

Comparisons of these different topographical models allowed the quantities of material extracted during the dredging campaigns, as well as the quantities of sedimentation for 4 yr (between 1997 and 2001 and from 2001 to 2002) to be estimated. Given the low proportion of organic matter and the homogeneity of the bedload lithology, the volumes were converted to mass using a bulk density of 1.6.

The sediment discharge of the Semois was also estimated from other dredgings, in order to validate the results obtained at Laviot (Table IV). Bedload transport was estimated from the record of the amounts of sediment dredged from the bed, taking into account that dredgings are systematically carried out in the same places, that these sites act as sediment traps and that control profiles are made before each dredging to ensure that the pits had been fully filled. For these sediment transport values, no topographical data were available. However, at least two successive dredgings had been carried out, the first serving as the reference for the date and location of the following dredging. The volume extracted during the second dredging divided by the time-lapse between the two allowed the volume deposited as well as the sediment discharge rate to be calculated. Evidently, this method is rather less precise than the former as it is based on the assumption that the trap was not filled entirely in the time between the two dredgings. We consider that the trap caught all of the bedload in transit. Therefore, the results obtained can only be a minimum estimation of sediment discharge.

 

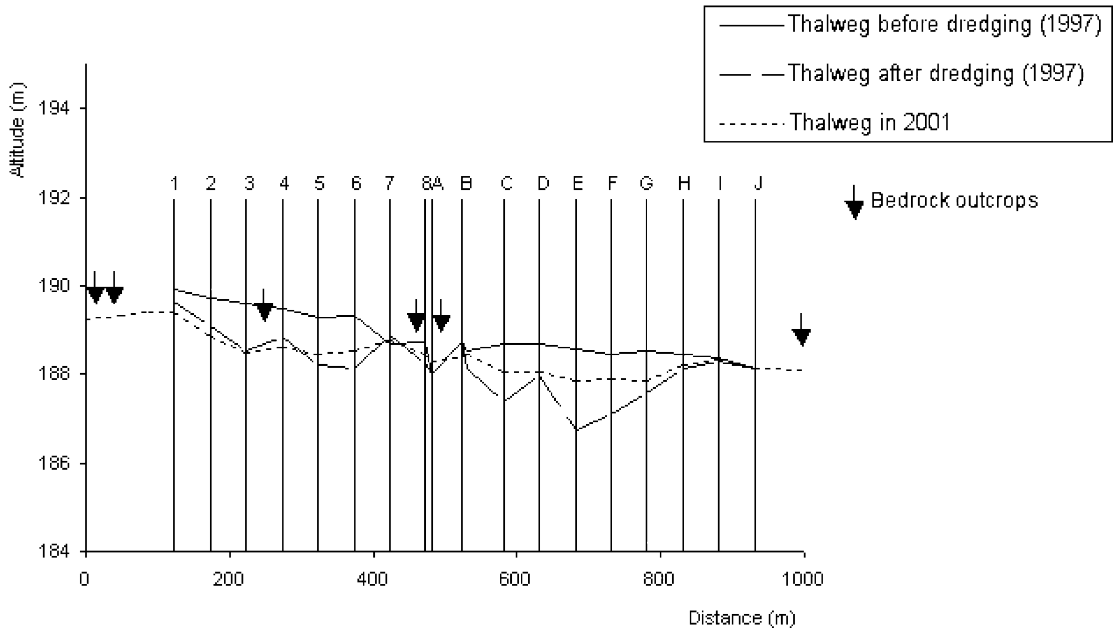


Figure 2. Long profile of the Semois in Laviot made in 1997 before and after the dredging and again in 2001, and location of the topographical cross-sections

*Sediment size*

Fieldwork was carried out along the length of the study section in order to define the morphometric and sedimentary parameters of the Semois. This data was essential for the application of the bedload transport formulae presented above. We worked at the basin and the study section scale, as well as on a finer scale—at the level of the sediment traps, which allowed sediment transport to be determined.

The grain-size distribution of the bedload of the main river and its tributaries was determined. Either the linear technique developed by Wolman (1954) or the photo-sieving technique developed by Ibbeken and Schleyer (1986) was used on the emerged bars, depending on the characteristics of the section. The latter technique entails

Table IV. Bedload transport in t $km^{-2}$ $yr^{-1}$ of several rivers of the Ardenne. These bedload transport have been determined from successive dredgings made systematically at the same places

| Site | Dates | Amount of sediment excavated ($m^3$) | Catchment area ($km^2$) | Sediment discharge (t $km^{-2}$ $yr^{-1}$) | Reference |
|---|---|---|---|---|---|
| Semois ardennaise | | | | | |
| Laviot | 1997–2001 | 11 200 | 1170 | 1.07 | |
| Bouillon | 1994–1997 | 3788 | 1075 | 1.4 | |
| Poupehan | 1994–1999 | 2765 | 1120 | 0.8 | |
| Vresse | 1997–1999 | 1856 | 1235 | 1.2 | |
| Ourthe (Famenne) | | | 1285 | 0.38 | Petit *et al*. (1996) |
| Ourthe (confluence) | | | 1597 | 0.45 | Petit *et al*. (1996) |
| Lower Ourthe | | | 2660 | 0.44 | Petit *et al*. (1996) |
| Amblève | | | 1044 | 0.43 | Petit *et al*. (1996) |
| Aisne | | | 190 | 2.07–3.23 | Houbrechts (2000) |
| Wamme | | | 139 | 2.21 | Petit *et al*. (1996) |
| Lhomme | | | 276 | 1.11 | Petit *et al*. (1996) |

 

photographing a zone of 1 $m^2$ through a grid of square sections (10 cm by 10 cm). Subsequently, the intermediate axes of the 100 elements situated beneath each intersection of the grid were measured.

When it was not possible to measure the grain-size distribution of emerged deposits, the elements of the surface layer of the riverbed were sampled under water in a zone of 1–2 $m^2$. This zone contains significantly more than 100 particles. Subsequently, the 30 largest elements of the sample were measured using slide callipers. The average size of the 10 largest elements from each sample was calculated. The largest element roughly represents the $D_{99}$, the five largest elements represent the $D_{96}$ and the 10 largest elements represent the $D_{90}$ (Carling, 1983).

A $D_{50}$ of 70 mm was decided upon for the different bedload transport equations. In the tributaries, as the grain size is slightly larger and bedload here consists of some large elements greater than 200 mm, the $D_{50}$ was of the order of 90 mm (Table I).

### *Tracers*

Two tracing campaigns were conducted during the hydrological seasons of 2000–2001 and 2001–2002 in order to determine, on one hand, the competence of the Semois and its tributaries and, on the other, the critical discharge. *In situ* painted pebble tracers (painting pebbles directly in the river bed, without disturbing them) were used at a number of sites. However, given the limited number of exposed ridges (even at low water level), it was also necessary to remove pebbles which were then marked with paint in a laboratory, before being reintroduced to the river (inserted tracers). In this case, we waited for a bankfull discharge (130 $m^3 s^{-1}$) to occur. This restructured the inserted material without technically mobilizing it (see below). The inserted pebbles had a diameter comparable to that of the river's bedload. This technique had the advantage of allowing the grain-size characteristics of the inserted elements to be predetermined and allowing the marked material to be introduced into the middle of the river, where bedload transport is greatest.

In order to increase the number of tracers recovered, Bunte and Ergenzinger (1989) suggested that iron should be introduced into the pebbles. For this study, lead was preferred, given its low melting point and its chemical stability in water. Only small amounts of lead were injected into pebbles so as not to greatly alter the density and hence their weight (after lead was injected into the pebbles, their average density was 3). These were also inserted into the river. Subsequently, pebbles containing lead and buried in the gravel sheet may be detected to a depth of up to 50 cm using a metal detector. Tests were conducted in order to determine the recovery rate of the inserted elements. In the Semois, 91% of the leaded pebbles and 56% of the painted pebble tracers were recovered. In one of the tributaries all of the leaded pebbles were found while only 13% of the painted pebble tracers were recovered. However, it should be pointed out that in this case, the pebble tracers travelled a longer distance and, compared with other inserted tracers, a greater proportion of smaller elements was used.

More than 3500 marked pebbles (*in situ* tracers, inserted painted pebble tracers, inserted leaded elements) were used at various sites along the Semois between October 2000 and February 2002. The different tracers were, in so far as was possible, taken up after every flood event. During this period the Semois experienced 13 flood events which exceeded the bankfull discharge (130 $m^3 s^{-1}$) but only two were really morphogenic (>180 $m^3 s^{-1}$). The most important of these, in January 2001, reached 350 $m^3 s^{-1}$, which corresponds to the 25-year flood (Table V).

Table V. Morphogenic floods of the Semois River that occurred between the dredging of 1997 and the 2001 profiles

| Flood | Peak discharge ($m^3 s^{-1}$) | Flood duration (h) | Recurrence (years) |
|---|---|---|---|
| 30.10.1998 | 296 | 108 | 6.5 |
| 14.12.1999 | 317 | 76 | 8 |
| 27.12.1999 | 229 | 42 | 2.5 |
| 7.01.2001 | 393 | 177 | 25 |
| 8.02.2001 | 231 | 28 | 2.5 |

 

*Discharge*

Unfortunately, it was not possible to install a gauging station on site. The nearest gauging station was located approximately 20 km downstream from the study section. Discharge at the study section, $Q$, was calculated from the gauged record using the formula:

$$Q = Q_g(a/A)^{0.8} \tag{7}$$

where $Q_g$ is the discharge measured at the gauging station, $A$ is the area of the catchment upstream of the gauging station and $a$ is the area of the catchment upstream from the study site. This method was used by the DIREN Rhône-Alps and is reliable for catchments with an area of less than 2000 km$^2$ (Bravard and Petit, 2000). It was considered suitable for this study as the distance between the two sites is only about 10 kilometres as the crow flies and the catchments are about the same size.

The sediment trap had been functioning between 1997 and 2002. During this time period the Semois experienced five mobilizing floods. The hydrographs for these floods were subdivided in order to determine the hourly duration of different discharge rates (180, 230, 270, 290, 320 and 360 m$^3$ s$^{-1}$), which were then introduced into the different sediment transport equations. It was possible to calculate the water levels using a permanent, one-dimensional, numerical flow model developed by the Laboratoire de recherche hydraulique du Ministère de L'Equipement et des Transports de la Région Wallonne. In this model the contribution of the flood plain is taken into account using a calculation for loss of energy per conveyance. The interaction between the low flow channel and the floodplain is taken into account using an adjustment of the conveyance of the cross-sections. When the bankfull stage is exceeded, an additional roughness, specific to the flood plain is considered. This model is based on a number of transversal cross-sections and water levels measured during three important floods (1993, 1995 and 2001). For a given discharge, it is then possible to calculate the maximum depth and the slope of the water surface for each point of the study reach (Gob *et al.*, 2003).

## RESULTS

*Critical discharge and estimation of the morphodynamic parameters*

The critical discharge was determined at 180 m$^3$ s$^{-1}$(at the station of Membre), even though the first signs of disturbance are already apparent at the bankfull discharge (130 m$^3$ s$^{-1}$). This may seem surprising when compared to other smaller rivers in the Ardenne, such as the Ourthe or the Lesse. Indeed, bedload mobilization occurs at a discharge of 0.4$Q_b$ for the lower Ourthe and 0.7$Q_b$ for the Lhomme, and at a discharge less than $Q_b$ for the Lesse (Petit *et al.*, 1996). However, this difference is counterbalanced by a greater bankfull discharge frequency in the Semois than in the other rivers of the northern Ardenne.

The Semois experienced five mobilizing floods (>180 m$^3$ s$^{-1}$) between the 1997 dredging and the topographical survey of 2001 (Table V). Among the peak discharges of these flood events, one was particularly important with a recurrence interval of 25 years. Between the surveys of 2001 and 2002 the Semois experienced only three flood events, which did not exceed 180 m$^3$ s$^{-1}$. Meanwhile cross-sections made at Laviot in 2002 (Figure 3) showed that the bed had not evolved greatly as compared to the previous year, even though the sediment trap created in the dredged zone had not yet been totally filled in and was therefore still functional. This led to the conclusion that this discharge (180 m$^3$ s$^{-1}$) corresponds well with the mobilization threshold.

The tracing campaigns indicated the size of material that may be mobilized. Indeed, at Dohan a $D_{50}$ of 85 mm, at Poupehan a $D_{50}$ of 73 mm and at Laviot a $D_{50}$ of 70 mm were mobilized by the flood of January 2002 (237 m$^3$ s$^{-1}$). In the tributaries, the $D_{50}$ mobilized is 61 mm on average and is never greater than the material that may be mobilized by the Semois. The inserted tracers also showed that during flood events, the distances travelled by the pebbles in the Semois are relatively long (up to 140 m for the tracers inserted at 'Dohan Île'). However, these long distances may simply reflect the size of the mobilizing flood (recurrence interval of 25 years). Indeed, for a number of weaker floods (winter 2001–2002), the maximal distance travelled by the elements inserted at the Dohan bridge is less than 30 m.

Different bedload transport equations were applied, introducing the parameters of width, depth, specific stream power, shear stress etc. calculated at cross-section 1 (Figure 3). This cross-section corresponds rather

 

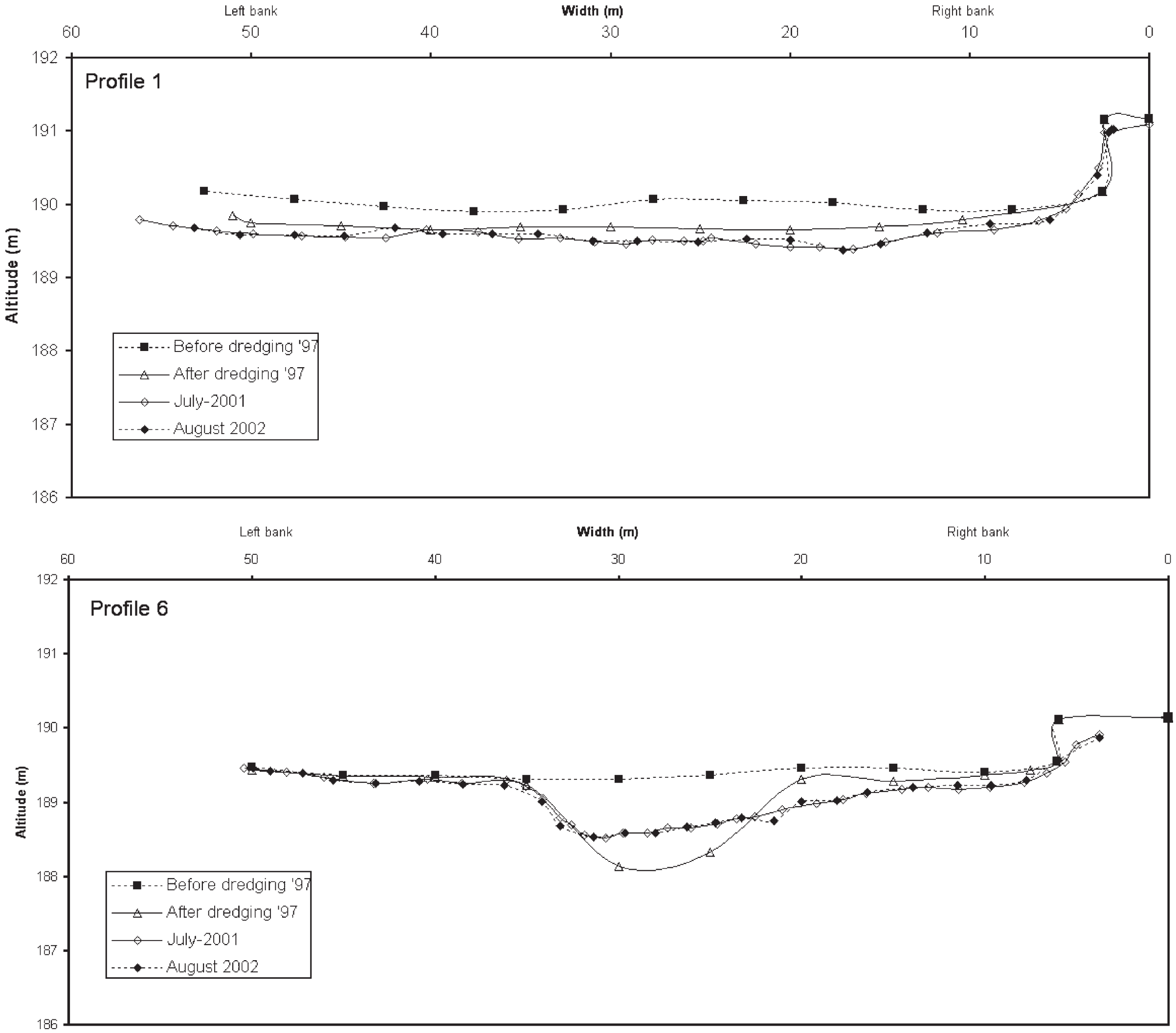


Figure 3. Cross-sections 1 and 6 of the dredged area in Laviot in 1997 before and after dredging, and again in 2001 and 2002. Cross-section 1 was hollowed slightly in 1997 and a small incision was made before 2001. A deep pit was made at cross-section 6 in 1997 with some in-filling until 2001. The riverbed did not evolve greatly between 2001 and 2002. Due to the vegetation, the left bank could not have been surveyed. It corresponds to the steep valley side and was not disturbed by the dredging

well with the initial situation prior to dredging because it was only slightly altered by the 1997 dredging. Thus, its dynamics are similar to those generally found in the Semois. At the level of the dredged zone and for a $D_{50}$ of 70 mm, the total shear stress is 21.9 N m$^{-2}$, 14.2 N m$^{-2}$ of which accounts for a critical grain shear stress corresponding to a Shields criterion of 0.019 ($\theta' = 0.012$). These values may seem quite low in comparison to the value of 0.030 generally proposed in the literature (Neill, 1968; Bravard and Petit, 2000). However, they are greater than those given by certain authors (0.015) for gravel-bed rivers (Ashmore, 1988; Clifford *et al*., 1992).

The unit critical discharge ($q_c$) is 3.39 m$^3$ s$^{-1}$ m$^{-1}$. The specific stream power is 31 W m$^{-2}$ at Laviot, which corresponds well with other rivers of the Ardenne: 16 W m$^{-2}$ for the lower Ourthe, 56 W m$^{-2}$ for the Hoëgne and 76 W m$^{-2}$ for the Lesse (to mobilize a $D_{50}$ of 70 mm for the first two rivers and 66 mm for the third). The differences observed between these watercourses may be explained by the fact that the Hoëgne and the Lesse are smaller. Also, there is greater bedform shear stress in these rivers and specific stream powers are therefore higher (Petit *et al*., 2000).

 

*Estimating quantities of trapped sediment*

Dredging along a 800 m stretch of the river caused the formation of a channel approximately 20 m wide and with a maximum depth of 1.8 m. Given the presence of ridges of bedrock, sediment could not be uniformly excavated from the entire section (Figures 2 and 3). The longitudinal section shows that two large pits are present, separated by a more resistant bank. The first cross-section (1) and the last two (I and J) show that the two riffles delimiting the study section were almost impossible to dredge. The creation of the channel gave rise to perched lateral deposits, which represent the undredged parts of the river. Since then, they have been disconnected from the river and are non-functional at low water levels. Dredging has led to the creation of large pits that play a role in trapping sediment. A comparison of the 2001 cross-sections with the cross-sections of the initial situation shows that there is only partial in-filling.

The quantity of dredged material and the quantity of material filling the pits was estimated by subtracting the different models (Plate 1). At Laviot, 11 200 $m^3$ of sediment, or 17 920 t, was extracted when the pits were cleared in 1997. This sediment was deposited on the floodplain to raise part of a campsite that was regularly flooded. Between 1997 and 2001, Plate 1 shows an in-filling of 5500 $m^3$ (8800 t) and erosion corresponding to 2730 $m^3$ (4730 t) for the entire section. The erosion indicates that part of the accumulated sediment does not originate upstream but from lateral adjustment of the river apparent from cross-section 6 (Figure 3). By subtracting local erosion from accumulation, the contribution from upstream corresponding to the sediment transport of the Semois may be estimated at 3130 $m^3$ or 5010 t. This corresponds to a specific sediment transport of 1.07 $t\,km^{-2}\,yr^{-1}$.

Table IV shows a comparison of sediment transport values for other parts of the Semois in the Ardenne region. Considering the reservations raised in the methodology section of this paper, the sediment discharge values of the Semois are relatively convergent and a value of 1.1 $t\,km^2\,yr^{-1}$ may be proposed. When this sediment transport rate is compared with the values in the literature (Petit *et al*., 1996; Houbrechts, 2000) one may observe that the sediment transport of the Semois is greater than that of the other rivers of the Ardenne region with a catchment of comparable size but less than that of the headwater streams (Table I). This observation may seem paradoxical but it can be explained by the morphological differences between the Semois and other rivers of the northern Ardenne.

As mentioned in the introduction, the sediment yield of the Ardenne rivers is relatively low when compared to rivers in other geomorphological settings. Thus, a recent study in the Southern Alps showed that the specific sediment transport rate of the Drôme was 38 $m^3\,km^{-2}\,yr^{-1}$ while its tributaries transport between 7 and 67 $m^3\,km^{-2}\,yr^{-1}$ (in other words between 11 and 110 $t\,km^{-2}\,yr^{-1}$ when a bulk density of 1.6 is used) (Liébault and Piégay, 2001; Liébault, 2003). In Catalonia, Batalla *et al*. (1995) recorded a sediment transport rate of 62 $t\,km^{-2}\,yr^{-1}$, while in Switzerland, Rickenmann (1997) measured a rate of over 200 $t\,km^{-2}\,yr^{-1}$. In semi-arid environments, with frequent flash floods, the rate can reach over 400 $t\,km^{-2}\,yr^{-1}$ (Reid *et al*., 1998).

*Estimating solid discharge from bedload transport equations*

Table VI highlights the different sediment transport rates obtained using the equations of Meyer-Peter and Müller, Schoklitsch, Bagnold and Martin presented earlier and applied to cross-section 1. With the exception of Bagnold's equation (1980) which differs substantially, the theoretical equations produce values of transported sediment for the Semois that range from 6147 to 10 571 t for the period between October 1997 and June 2001. These estimations are relatively close to the values observed. According to the topographical survey the sediment trap created from dredging at Laviot was filled with 8800 t of sediment between 1997 and 2001 (5010 t if sedimentary flux alone is considered).

As Gomez and Church (1989) have already demonstrated, the equations of Bagnold (1986) and Schoklitsch (1934) provide the most accurate estimations. The observed and the calculated values are relatively close even if the formulae, with the exception of Bagnold's (1980), lead to a slight overestimation of the calculated values in comparison to those observed. A number of factors may explain these differences. The sediment transport equations give a potential value of sediment discharge, considering that there is a sufficient quantity of movable material. In this regard, attention must be drawn to the fact that, during the considered time period (4 yr), there were a particularly large number of mobilizing floods and floods with elevated recurrence levels, many of which were of remarkably long duration (e.g. the mobilization threshold was exceeded for 8 days during the flood of October

 

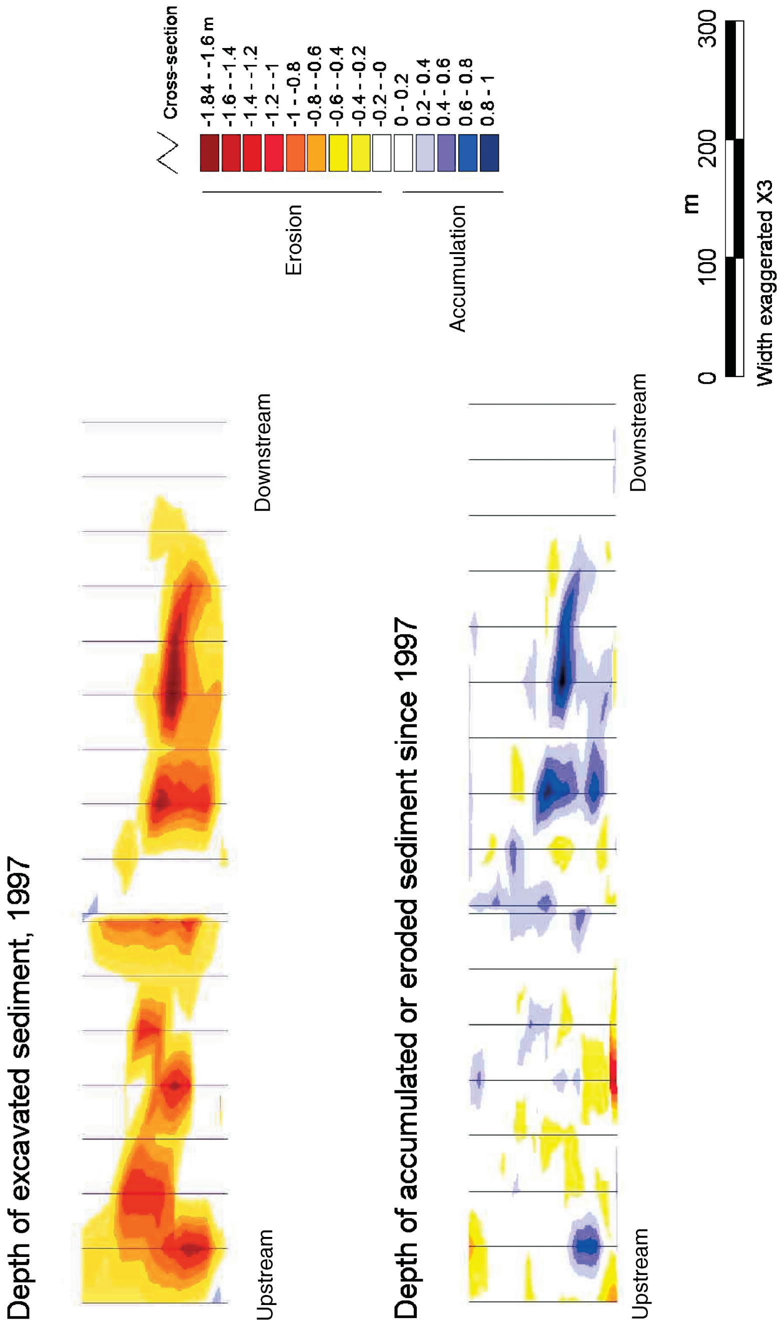


Plate 1. Sediment balance of the dredging area from 1997 to 2001

Table VI. Bedload transport of the Semois in Laviot for the period 1997–2001 determined by different transport equations and by a sediment trap (dredging of Laviot). Values are expressed in tonnes

| | Meyer-Peter equation (1) | Schoklitsch equation (2) | Bagnold 1977 equation (3) | Bagnold 1980 equation (4) | Bagnold 1986 equation (5) | Martin 2003 equation (6) | Sediment trap |
|---|---|---|---|---|---|---|---|
| October 98 | 2413 | 1984 | 2241 | 5663 | 2002 | 3539 | |
| December 99 | 1659 | 1372 | 1561 | 3944 | 1395 | 2473 | |
| December 99 | 567 | 537 | 510 | 1290 | 456 | 1268 | |
| January 01 | 3071 | 1896 | 2588 | 6542 | 2313 | 2446 | |
| February 01 | 377 | 358 | 340 | 859 | 304 | 845 | |
| Total | 8087 | 6147 | 7240 | 18298 | 6470 | 10571 | 8800 |

1998) (Table V). It is therefore appropriate to examine whether the contribution of material from the valley sides and tributaries is sufficient and whether the stock of mobilizable material had the time to regenerate between mobilizing floods. The provision of sediment to the Semois may be considered to be relatively weak, as even though the river is regularly in contact with the valley sides this does not seem to contribute greatly to the bedload. Moreover, though the tributaries provide the Semois with gravelly material comparable in size to that transported by the river, their small number and the restricted area of their watersheds mean that they only provide a limited contribution. After rapid calculation this may be seen to represent only about 15% of the Semois sedimentary flux. Finally, the contribution from upstream is subject to the same uncertainties as the sector analysed and lateral erosion is very limited. All of these elements lead us to believe that the Semois recharges at a relatively slow rate, with numerous bedrock outcrops preventing incision by the river.

### *Impacts of dredging*

The different topographical surveys and the estimates of sediment transport in the Semois suggest that the use of dredging as a means of flood prevention is only a provisional solution, as in less than 10 yr the bed is expected to assume its initial shape once more. In addition, the hydrological study mentioned earlier showed the ineffectiveness of this technique as, following dredging, the reduction of the water level in times of flood is minimal. From an ecological point of view, a study conducted in parallel with this study underlined the very harmful effects of this type of sediment extraction. By disturbing the bedload and the conditions of flow, dredging may disturb habitats and lead to the impoverishment of flora and fauna (Gob *et al*., 2003).

This study has analysed the consequences of a dredging campaign that was greater in scale than the dredgings carried out in the other rivers of the Ardenne. However, dredging in the Semois is only of minor importance when compared with the extractions made from rivers in other geomorphological contexts, such as in Poland, in Italy or in the south of France. In 10 yr, only about 30 dredging campaigns, accounting for less than 35 000 $m^3$, have been recorded on a 40-km stretch of the Semois.

## CONCLUSIONS

The large incised meanders of the Semois mean that its river system is clearly different from the other, better-known rivers of the northern Ardenne Massif. The Semois is characterized by the restricted nature of its floodplain that prevents the formation of free meanders, by a limited number of emerged deposits at the low water level and by the presence of numerous bedrock outcrops in the low flow channel. This influences the morphology of the low flow channel. Hence, in relation to the rivers of the northern Ardenne, such as the Ourthe and the Lesse, the average depth of the Semois at bankfull is lower, its width/depth ratio lower (c. 30) and its bankfull discharge is attained more rapidly and therefore more frequently.

With a view to managing sedimentation, the mobilization discharge was calculated and the quantity of material mobilized was estimated. This was done in order to better understand the impacts and effectiveness of the dredging and hence determine the rejuvenation rate of the features. The bedload mobilization discharge in the Semois is greater than the bankfull discharge. This is in contrast to the observations made in the northern Ardenne, where mobilization may be observed for floods clearly less than the bankfull ($0.5Q_b$). The total shear stress and the specific streampower (at the bankfull discharge and for floods with a high recurrence interval) are less than those of the rivers in the northern Ardenne. But, in the Semois, the total roughness is lower than in rivers of comparable dimensions (Manning's total roughness coefficient is barely 0.045 compared with 0.60 for the lower Ourthe). In the breakdown of total shear stress, the bedform shear stress is lower in the Semois, leaving a greater availability of grain shear stress which is involved in the mobilization and transport of sediment. The lower roughness of the Semois may be explained by the fact that the alternation of bedforms is not as developed, by the absence of free meanders and by the limited depth linked to numerous bedrock outcrops. This implies that the quantities transported in the Semois ($1.1\,t\,km^{-2}\,yr^{-1}$) are greater than those of rivers of the same size in the northern Ardenne (between 0.4 and $0.5\,t\,km^{-2}\,yr^{-1}$). Moreover, the greater width of the low flow channel in the Semois (see width/depth ratio) assures a wider band of active transport.

The Laviot dredging, given its amplitude and the techniques employed, acted as a sediment trap. Between 1997 and 2000 the pit was partially filled with $5500\,m^3$ of sediment, despite the occurrence of numerous mobilizing floods. From the extent of sedimentary flux, a return to the initial state of the riverbed (before dredging) may be expected after approximately 10 yr. Despite the large scale of dredging for this type of river, it is only a temporary solution in terms of flood prevention. Furthermore, its effects on flood levels are also limited. The reduction of the water level in times of flood is only a few centimetres as bedrock outcrops limit the depth that may be reached by gravel mining.

From a comparison with other rivers where gravel mining has been documented, the dredging of the Semois may be considered to have had a more limited impact even if, from an ecological point of view, it has been shown to be detrimental. The quantity of sediment extracted from the Semois is not comparable to that taken from the rivers of the French Alps, Italy or Poland. Here, the time required in order for the riverbed to return to its initial situation is estimated at many tens of years and in some cases the threshold of irreversibility has been breached. Besides, the dredging of the Semois has not resulted in incision of the river system, given the many bedrock outcrops. Instead, these act as a control for the level of the riverbed, strongly limiting the effectiveness of dredging with regard to flood prevention.

*Notation*

| | |
|---|---|
| $a$ | Catchment area upstream of study site ($km^2$) |
| $A$ | Catchment area upstream of gauging station ($km^2$) |
| $d$ | depth (m) |
| $D$ | bed material size (m) |
| $d_r$ | reference value of $d$ (Bagnold formula) |
| $D_{50}$ | median bed material size (m) |
| $D_{50}$, $d$ | mode size of bed material (m) |
| $D_r$ | reference value of $D$ (Bagnold formula) |
| $g$ | acceleration due to gravity |
| $g_b$ | bedload transport rate per unit channel width ($kg\,m^{-1}\,s^{-1}$) |
| $\gamma_f$ | specific density of fluid ($kg\ m^{-3}$) |
| $\gamma_s$ | specific density of sediment ($kg\ m^{-3}$) |
| $i_b$ | specific bedload transport rate for a size fraction ($kg\,m^{-1}\,s^{-1}$) |
| $i_{br}$ | reference value of $i_b$ (Bagnold formula) |
| $q$ | unitary discharge ($m^2\,s^{-1}$) |
| $q_{cr}$ | critical unitary discharge ($m^2\,s^{-1}$) |
| $Q$ | discharge at study site ($m^3\,s^{-1}$) |
| $Q_g$ | discharge at gauging station ($m^3\,s^{-1}$) |
| $Q_b$ | bankfull discharge ($m^3\,s^{-1}$) |
| $\rho$ | density of the fluid ($kg\,m^{-3}$) |
| $S$ | slope ($m\,m^{-1}$) |
| $\theta_c$ | critical dimensionless shear stress |
| $\tau$ | total shear stress ($N\,m^{-2}$) |
| $\tau'$ | grain shear stress ($N\,m^{-2}$) |

 

$\tau''$ bedform induced shear stress ($N\,m^{-2}$)
$\tau_{cr}$ critical sheal stress for particle entrainment
$\tau_{cr}$, $\tau_0$ critical shear stress for bed particle entrainment ($N\,m^{-2}$)
$\omega$ specific stream power ($W\,m^{-2}$)
$\omega_0$ critical specific stream power ($W\,m^{-2}$)

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