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IMPACT OF HYDROELECTRIC POWER RELEASES ON THE MORPHOLOGY AND SEDIMENTOLOGY OF THE BED OF THE WARCHE RIVER (BELGIUM)

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ABSTRACT

The Butgenbach dam on the Warche River was built in 1932 in order to maintain a sufficient supply of water to the Robertville reservoir situated 7 km downstream, for the production of hydroelectricity. During winter months, releases are made almost every day from the Butgenbach dam. From a hydrological point of view, this has resulted in significantly reducing the number of discharges that are higher than bankfull. Despite the reduction in peak discharge, there is a significant increase in the number of efficient discharges (0·6 bankfull). The impacts of these hydrological modifications on the bed morphology and sedimentology below the Butgenbach dam have been studied and the following geomorphological modifications have been identified: a doubling of the width of the channel in 45 years, a reduction in the number of riffles and pools, an increase in the number of gravel bars and islets and an increase in bedrock outcrops in the channel. Moreover, the finest bed particles are mobilized by the almost daily releases, inducing a significant increase in bed-material size sorting. The reduction of sinuosity and the disappearance of bed differentiation and riffle/pool sequences have produced a diminution of bed roughness and an increase of the competence of the river. Thus relatively small floods can remove the armoured layer. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: gravel-bed river; flow regulation; channel adjustment; sediment transport, armoured bed

INTRODUCTION

The past century has witnessed the building of more and more dams throughout the world (Benn and Erskine, 1994; Dynesius and Nilsson, 1994; Zhong and Power, 1996; Astrade, 1998; Graf, 1999; Brandt, 2000). Parallel to this there has been an ever-increasing number of studies undertaken with regard to their impacts on hydrology, morphology and sedimentology as well as on fluvial flora and fauna (Kellerhals and Gill, 1973; Walker *et al.*, 1978; Petts, 1979, 1980, 1984, 1987; Petts and Lewin, 1979; Williams and Wolman, 1984; Chien, 1985; Walker, 1985; Carling, 1988; Klingeman *et al.*, 1994; Vivian, 1994; Weingartner and Aschwanden, 1994; Maheshwari *et al.*, 1995; Sear, 1995; Power *et al.*, 1996; Friedman *et al.*, 1998; Erskine *et al.*, 1999; Surian, 1999; Merritt and Cooper, 2000). Even though certain authors have proposed general models for the response of rivers to the disturbance induced by dams, it emerges from these studies that the impacts of such constructions differ greatly (Petts, 1980), depending on the location, the environment, the substrate and the system of water and sediment release (Brandt, 2000).

In Belgium the rate of dam construction has not been as fast as that of other countries. However, many dams were erected during the first half of the 20th century, notably for the production of hydroelectric power. Still, no studies have yet been undertaken on the hydrological and morphological impacts of these works on watercourses. The aim of this study, therefore, is to analyse the impacts of the Butgenbach dam on the morphology and sedimentology of the Warche River. The impacts on the hydrological conditions and on fluvial flora and fauna have been examined elsewhere (Assani *et al.*, 1999; Assani *et al.*, unpublished work).

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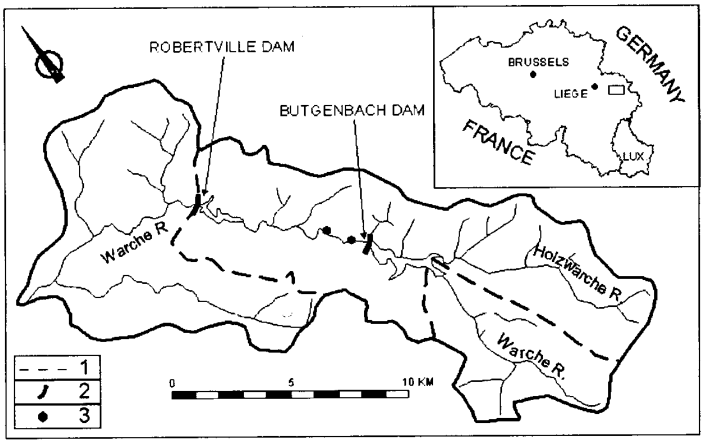

Figure 1. The Warche catchment area: 1, limit of the sub-basins; 2, location of dams; 3, location of the two reaches in Figure 4

This study concerns a 7 km long stretch of the river below a dam constructed in 1932 to ensure an optimal supply of water for the production of electricity at another reservoir downstream (Figure 1). Large releases (equivalent to 0·6 of bankfull discharge) are made very regularly (almost every day in winter). In this study we shall consider the consequences of these modifications on the hydrological system and the sedimentation of the bed as well as the spatial and temporal changes to the channel morphology.

SITE OF STUDY

The hydrographical basin of the Warche River overlies the schist rocks (schists, phyllites and quartz phyllites) of the lower Devonian, in the northern Ardenne (Belgium). The catchment areas above the Butgenbach and Robertville dams are 80 km^2 and 118 km^2 respectively (Table I). The Butgenbach Lake submerges the confluence of the Warche and the Holzwarche and only small tributaries join the Warche between the two dams.

In natural conditions, the Warche follows the typical model of rivers in the Ardenne region. It consists of a gravel-bed river, in a single well-defined channel with a floodplain reaching up to 40 m in width. The floodplain consists of compacted silts 1 to 2 m thick, covering a pebble layer which rests on the bedrock. Rivers rarely come into contact with the bedrock even in the deepest pools, but flow over the gravel layers put down during the last cold period (Petit, 1995). Field observations give the bankfull discharge as 15 m^3 s^{-1}. The bankfull discharge recurrence interval for rivers of this size is 0·6 years in natural conditions (Petit and Pauquet, 1997). The catchment area is mainly covered by forest and grass, which explains why (as is the case of other rivers of the Ardenne Region) there is a low quantity of suspended material transported by the river (around 20 t km^{-2} a^{-1}: Lemin *et al.*, 1987).

Table I. Features of the Butgenbach dam catchment area

	Upstream	Downstream
Surface area (km^2)	80	118
Slope (m m^{-1})	0·0045	0·0042
Bankfull discharge (m^3 s^{-1})	8	15
Width (m)	5·4	14·7
Depth (m)	0·87	0·87

Table II. Impacts of the Butgenbach dam on floods of the Warche (1930–1997)

Intensity of flooding	Frequency of flooding	Duration of flooding
Major floods ($\geq Q_{10}$)	Total disappearance	Total disappearance
Very large floods (Q_{10}, Q_5)	Lessening	Lessening
Large floods (Q_5, Q_1)	Large reduction	Large reduction
Medium floods (Q_1, $0{\cdot}5Q_1$)	Reduction	Reduction
Minor floods ($0{\cdot}5Q_1$, Q_m)	Strong increase	Strong increase

Q_{10} = 10-year flood; Q_5 = 5-year flood; Q_1 = annual flood; Q_m = mean annual discharge.

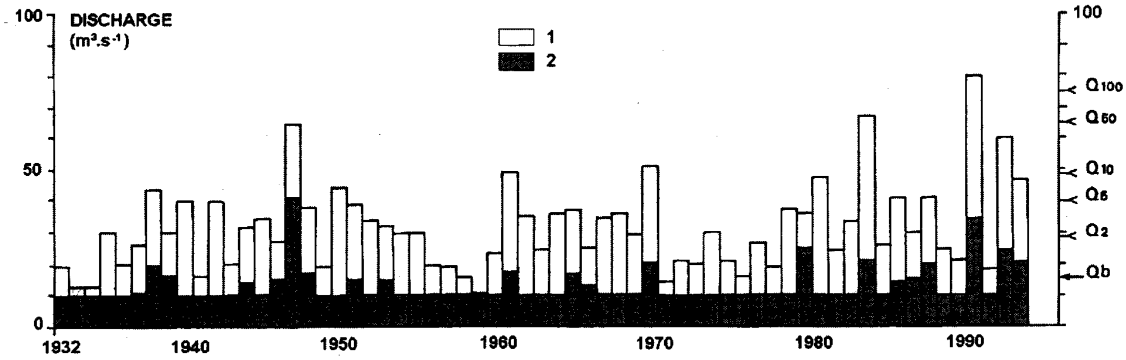

Figure 2. Annual maximum flood series at Butgenbach on the Warche: 1, reconstructed natural discharge; 2, regulated discharge below the dam. The y-axis to the right details characteristic discharges: Q_{100} = 100-year flood, Q_{50} = 50-year flood, Q_{10} = 10-year flood, Q_5 = 5-year flood and Q_b = bankfull discharge

MODIFICATIONS TO THE WARCHE HYDROLOGICAL SYSTEM

The unregulated discharge (Q_u = discharge if the dam had not existed) has been reconstituted from the daily evolution of the water level in Butgenbach Lake, and from the discharge released from the dam. The recorded series for the period between 1932 and 1995 can be used in different applications, such as in the Gumbel distribution for the annual maximum to determine the recurrence interval for major floods (Assani *et al.*, 1999).

The impacts on the flood regime are summarized in Table II. Figure 2 compares the inter-annual variability of floods during, on one hand, the reconstituted natural regime (Q_u) and on the other hand, during the regulated regime (Q_r). A comparison of the natural discharges (Q_u) with the regulated discharges (Q_r) reveals the extent of modifications to the Warche hydrological system. The frequency of discharges of 10 m^3 s^{-1} (which correspond to the normal release) has been multiplied by at least 50 times. These releases are mainly made in winter as part of the reservoir management for the production of electricity. However, the frequency of discharges superior to the bankfull discharge has been reduced by a factor of at least ten. Comparisons between the maximum discharges of the regulated regime (Q_r) and those of the original natural conditions (Q_u) show a drastic reduction in peak discharge downstream from the dam (Figure 2). Thus, the maximum discharge released since the construction of the dam is lower than the 10-year flood whereas it would have reached the 100-year flood in the absence of the dam.

STUDY METHODS

The study of changes to channel morphology since the construction of the dam has been undertaken using large-scale maps (1 : 1000 and 1 : 1250) of 1951 and 1966, aerial photographs (1954, 1971 and 1984 at a scale between 1 : 15 000 and 1 : 25 000) and cross-sectional profiles made in 1966 (more than 100 with a middle inter-distance of 50 m). Levelling of the same sites was carried out in 1996 permitting comparisons between the surveys.

The geomorphological evolution of the different bedforms was followed for five years (1993–1997). The size of the islets (height, width, length) was recorded regularly. Experiments with marked pebbles were conducted at ten different sites in order to determine the discharge required to cause bedload movement, and therefore its frequency. The hydraulic parameters which caused the motion of bed material were also measured: the total shear stress was determined from the product of the energy slope and the hydraulic radius; the grain shear stress was estimated using the relationship between roughness due to resistance of particles (known by means of the Strickler formula) and the total roughness in Manning's equation. This method, recommended by Richards (1982), has been successfully tested in the rivers of the Ardenne (Petit, 1990).

Most of the observations were concentrated downstream of the Butgenbach dam. In order to have some reference values, similar observations were also conducted above the dam using the same methodology. Granulometric analyses were carried out at 21 sites upstream from the dam and at 16 sites downstream from the dam. The quantity measured varied between 80 and 500 kg, depending on the size of the material. This was due to the fact that a sample is required to be at least 50 times the weight of its coarsest element (Mosley and Tindale, 1985; Church *et al.*, 1987). In order to have a reasonable idea of the competence of the river, the b-axis of the 30 biggest pebbles was measured, in accordance with the methodology proposed by Bluck (1982), and applied by Gautier (1994).

RESULTS

Morphological modifications

The longitudinal variation of the average width and depth at bankfull stage measured in 1966 were analysed by means of the Mann–Kendall test. This is a non-parametric test used to detect significant changes in the average of hydro-climatic series (Sneyers, 1975; Vannitsem and Demarée, 1991). Its application to the values of width and depth did not highlight any significant modification of these variables downstream of the Butgenbach dam (Figure 3).

This is due to the fact that below the dam the Warche does not have any tributaries that contribute a significant amount of discharge or bedload that might affect the morphology of the river. It does show, however, that the incision and widening of the channel is no more important just below the dam, than even further downstream. In other words, the whole of the 7 km long stretch below the dam has reacted in the same way, as far as width and depth are concerned. It is therefore likely that the dam has had an influence on the whole section.

Changes in the width over time were established from the comparison of measurements taken in 1953, 1966 and 1996. Changes in depth between 1966 and 1996 were also examined and analysis was conducted using the Student *t*-test (Table III). It emerges that even though the average width has more than doubled in 45 years the rate of increase of width has been relatively constant (0·18 m a^{-1} between 1951 and 1966; 0·16 m a^{-1} between 1966 and 1996). Meanwhile, the depth has not changed significantly between 1966 and 1996.

This considerable widening results, first of all, from the classical processes of lateral erosion. This is exacerbated by the frequent releases which are very efficient in terms of bank erosion. A second process involves the formation of islets, of which four stages of development can be observed (Figure 4).

Table III. Average width and depth of the Warche below Butgenbach dam between 1951 and 1996

	1951	1966	1996	*t*1	*t*2
Width (m)	7·30 (81)	9·95 (81)	14·70 (81)	7·0114*	9·9635*
Depth (m)	–	0·856 (81)	0·870 (81)	–	0·3445

*t*1 = value of Student *t*-test for comparison of the averages for 1951 and 1966.
*t*2 = value of Student *t*-test for comparison of the averages for 1966 and 1996.
* significance level of 5 per cent.
Numbers in parentheses indicate number of measuring stations.

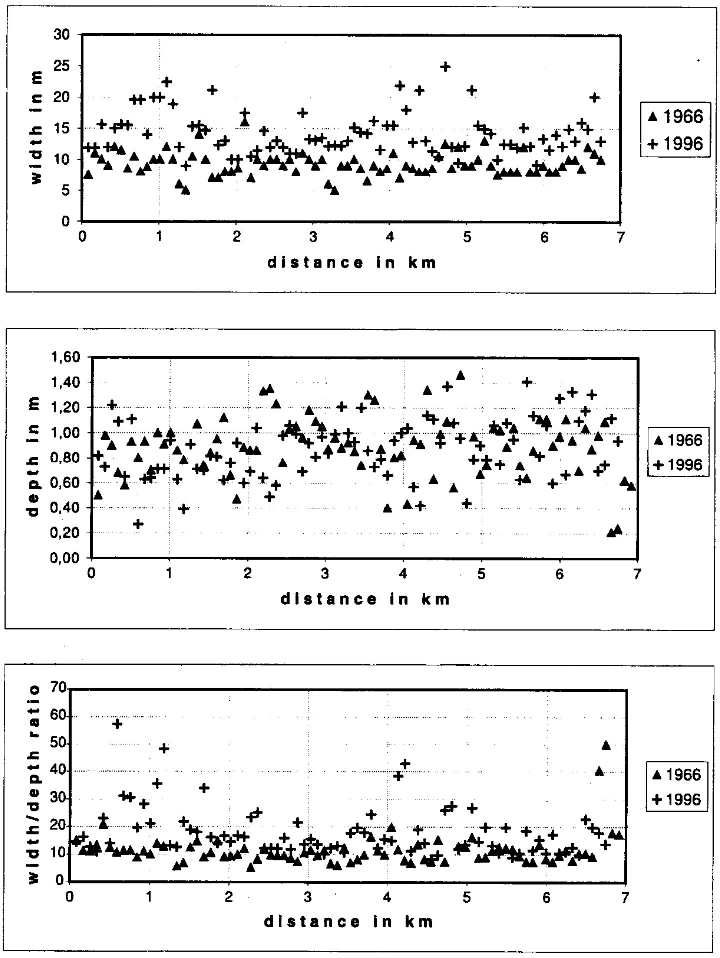

Figure 3. Longitudinal variation of width, depth and width: depth ratio of the Warche downstream from the Butgenbach dam

(i) The scalping of the carpet of vegetation allows the incision of small cut-channels in the floodplain which give rise to the formation of an islet (stage A in Figure 4).

(ii) The erosion of the top surface of the islet reduces its height below that of the banks (stage B in Figure 4). The islet reaches a level sufficiently low (about 50 cm above the bottom of the bed) to be progressively covered by gravel transported during higher discharges. The gravel serves as an implement for digging numerous channels at various depths over the surface of the islet.

(iii) The next stage is characterized by the development of the channels, many of which converge further downstream. The channels fill with pebbles that intensify the erosion of the finer materials of the islet (stage C in Figure 4).

(iv) After the inter-connection of the channels, the islet is transformed into a gravel bar. This may be partly colonized by sub-aquatic vegetation of a completely different type to that of the initial floodplain. (Assani *et al.*, unpublished work). At the site of the islet, the river is enlarged considerably, forming different threads (stage D in Figure 4). Thus a braided river pattern is formed from features initially created by erosion and then evolving by aggradation of the bedload. Finally the river manages to sweep and remove the whole of the floodplain, which practically disappears.

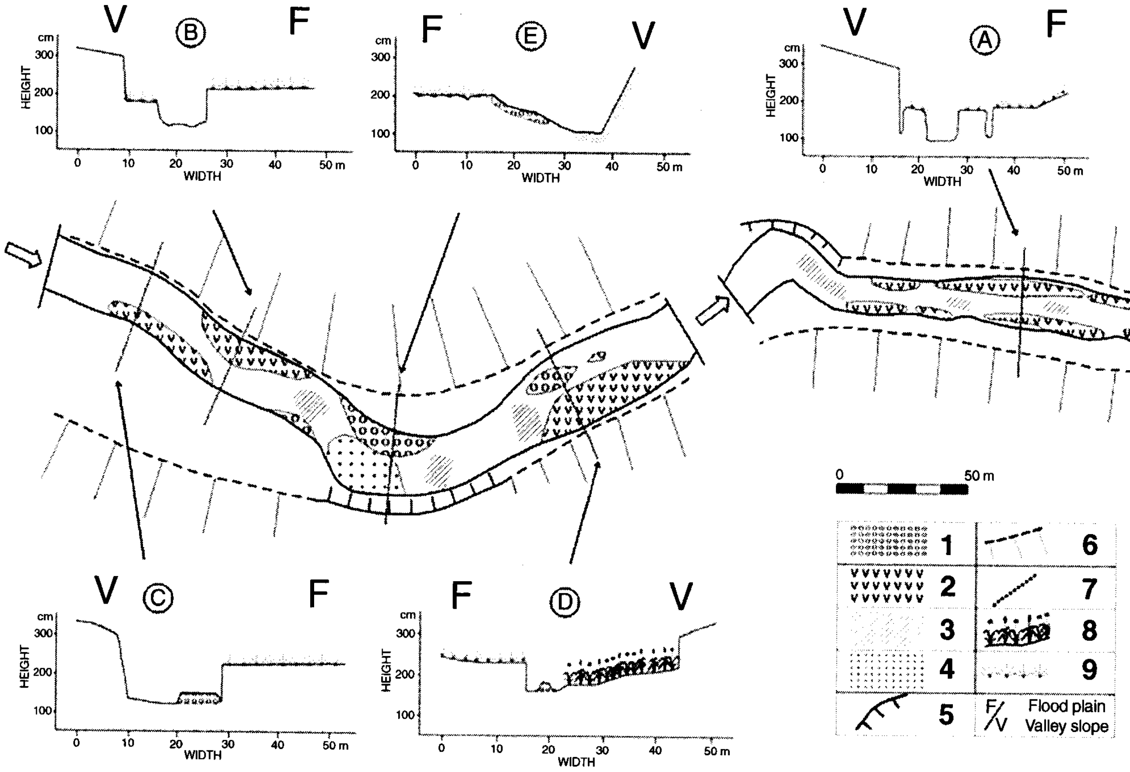

Figure 4. The reaches of the Warche with the location of islets in different stages of evolution and the bedrock outcrops in the riverbed and on the valley sides. Key: 1, gravel bars and islets without vegetation; 2, islets and bars with vegetation; 3, bedrock outcrops in the bed of the river; 4, filled pools; 5, steep valley sides with outcrops of rock; 6, limit of the floodplain and gently sloping valleys; 7, location of cross sections (A to D represent stages of islet development); 8, gravel bars with subaquatic vegetation (on the cross-section); 9, islets with floodplain vegetation (on the cross-section)

The process of islet formation has been found in other rivers of the Ardenne (Petit, 1984; Molitor, 1991) but without evidence of significant river widening. In this case study, there is a supplementary factor that intervenes: the absence of sand and silt particles to fill the channels. This results firstly from the reduction of suspended sediment transport below the dam and also from the rapid fluctuations in discharge. Indeed, during releases, flow velocities are too great to allow the sedimentation of fine particles transported in suspension. The compensation discharge returns shortly after the release and does not allow the islets in formation to be submerged for a long time, which deters the sedimentation of fine particles in the cut-channels.

According to comparison of average depths of the channel between 1966 and 1996 (Student t-test not significant at 5 per cent level; see Table II) there has been no significant change in the depth of the river in 30 years. Unfortunately no earlier data are available (1930–1966) to indicate what conditions were like just after the construction of the dam. However, different indicators show that there has been incision of the river. There are outcrops of rock that appear regularly in the river bed all along the section below the dam and large river potholes dug into the bedrock. Gravel layers that can be seen in the banks indicate the old bed-level which is higher (0·5 to 1 m) than the present level. In rivers that are not incising it has been noted that these gravel layers tend to be at the same level as the present bed (Petit, 1987). The level of gravel layers in the Warche indicates that incision took place. However, this is likely to have ceased relatively quickly, soon hitting the bedrock because the removable sediment layer was not very thick (1 m). On the other hand, the selective movement of the smallest particles due to changes in the hydrological system (see below) has led to the formation of an armoured bed that inhibits further incision.

Comparisons of the course of the Warche between 1951 and 1996 reveal that it has been reduced in length due to the cut-off of a large meander. The cut-off had started in 1951 and was finally achieved by 1984. It shortened the length of the course of the river between the dams by 4 per cent. Cutting-off of other smaller bends has also been observed, reducing the overall length of the course.

The analysis of the bedform shows a drastic reduction in the number of riffles and pools below the dam, compared to the reach of the river above the dam (Table IV). However, there is an increase in the number of gravel bars and islets and thus a tendency for the channel to take on a braided pattern. A reduction of the alternation of bedforms has lowered the total roughness of the river bed. Indeed, the Manning coefficient for roughness (calculated at the bankfull stage) is as little as 0·036 for the lateral bars, 0·048 on the islets, and 0·052 on convex bars. The highest value was for the middle bars at 0·055. These values are distinctly less than for other rivers of the same size in the Ardenne (Petit, 1990). The reduction in roughness means that the total shear stress is decreasing in terms of the bedform shear stress while the grain shear stress, a major factor in bedload transport, is increasing. In other words, the river can achieve bedload movement with less total shear stress.

Modifications of the bed sedimentology

Granulometric analysis revealed that the size of materials below the dam was clearly larger than above it. The median diameter was three times greater (Table V). The increase in the size of material in the section below the dam is a result of the small particle erosion caused by the increased frequency of discharges of the order of 10 $m^3 s^{-1}$. Observation of the marked pebbles indicated that the releases are able to mobilize part of the bed material. Altogether about 200 pebbles had moved (D_{50} = 28 mm, D_{90} = 57 mm, D_{99} = 90 mm) for a total shear stress of 22 N m^{-2}, a grain shear stress of 17 N m^{-2} and a specific power of 26 W m^{-2}.

The selective transport of the finest bed material created an armoured bed downstream, inhibiting incision. This conforms with results of earlier studies by Petts (1984). Furthermore, the sorting index values (Table V) indicate that the erosion of the finest bed particles confers good sorting of the bed material in comparison with the material upstream from the dam. This process of selective sorting has affected the subsurface layer. The

Table IV. Developed features of the river bed above and below Butgenbach dam in 1996

	Riffles/pools	Islets	Bars	Outcrops of rock	Length surveyed (km)
Above dam	368	5	0	1	11
Below dam	9	48	29	13	7

Table V. Comparison of granulometric characteristics in the Warche riverbed, above and below Butgenbach dam (in millimetres)

	D_{10}	D_{50}	D_{90}	Sorting index [Otto index]
Above dam	5·2 (21)	37·3 (21)	75·7 (19)	1·39 [21]
Below dam	56·9 (16)	115·9 (16)	199·7 (15)	0·73 [16]
Student *t*-test	11·1753*	7·6576*	6·8861*	11·9515*

Numbers in parentheses indicate number of samples.
* Significant at 5 per cent level.

Table VI. Comparison of the size (in millimetres) of surface and subsurface materials above and below Butgenbach dam (*n* = number of samples)

		D_{90}	D_{50}	D_{10}	*n*
Above dam	surface	73·8	33·1	4·3	8
	subsurface	52·9	14·7	0·52	8
Below dam	surface	185·8	108·0	54·0	8
	subsurface	177·1	98·1	44·6	8

difference in the size of material between the different surface and subsurface layers is very noticeable above the dam, whereas below the dam the difference is not marked (Table VI).

Observations taken below the dam after a discharge of 20·5 $m^3 s^{-1}$ (with a recurrence interval of less than 2 years in the uncontrolled regime) show that material is generally transported in all 12 of the sites where there were marked pebbles. The size of the largest pebble moved is 312 mm, and the average of the ten largest particles moved is 153 mm. This indicates that for such a discharge the bed material is transported by a specific power of about 55 W m^{-2}. Erosion of the surface layer enables the removal of the fine particles of the subsurface layer. As this departure is not compensated by the renewal of fine particles from upstream (that could have assured the percolation of fine particles through the surface layer) there is consequently a progressive impoverishment of fine elements in the subsurface layer.

The removal of the whole of the bed material for such a frequent discharge is rather rare, and is not often observed in other rivers of the Ardennes. On the river Rulles, which meanders considerably, the coarsest particles (70–100 mm) that are found in the bottom of the pools were not moved in response of the 10-year flood with a unit stream power exceeding 60 W m^{-2} (Petit, 1987).

The competence of the Warche above the dam was assessed by recording the average size of the 30 coarsest particles on the riffles, just after the flood of December 1993 (recurrence interval of 50 years). It is possible that this material has either been deposited or resisted being moved by the flood. This is then an accurate estimation for the competence of the river during the flood (Bravard and Petit, 1997). The size of the material measured in the 30 or so sites varies between 120 mm and 190 mm. This is almost half of the size of the particles transported in the section below the dam for much less significant floods. It is apparent that despite the flood control, the dam has been responsible for an increase of the competence of the river, as a result of the disappearance of the bedform.

DISCUSSION AND CONCLUSION

This study is based on the comparison of measurements taken from maps and those taken directly on site. Such comparisons may lead to a certain number of errors due to the difference in the scales of measurement used for width and for depth. Two types of errors are possible: errors related to the precise location of transverse profiles shown on the maps and errors related to determining the exact width and depth which correspond to the bankfull stage at different times of measurement. With regard to the first type of error it is possible that, at the time the measurements were taken on site in 1996, all of the transverse profiles and the points of measurement for each of the transverse profiles represented on the maps of 1951 and 1996 may not have been precisely located. Thus errors may result in the measurement of width and depth at the bankfull stage. However, in our case this type of error may be considered as not very significant for the following main reasons.

(i) The maps of 1951 and 1966 were very precise due to their large scale (1 : 1000 for width and 1 : 100 for depth). It ensues that errors relating to the location of transverse profiles may not exceed 2 m (2 mm on the map) with regard to width and 0·2 m (2 mm on the map) with regard to depth. In our opinion this margin of error is negligible, given the poor differentiation of the bed due to the disappearance of riffles and pools and the poor longitudinal variation of width.
(ii) Our analysis is based on comparison of the averages of width and depth at the bankfull stage. This method reduces errors relating to the location of transverse profiles and also to the points of measurement of the depth of each transverse profile. It is justified by the fact that the width of the river has almost doubled in 45 years. Had the direct comparison of transverse profiles taken at different times been used, this may have led to greater errors relating to width and depth at the bankfull stage.
(iii) Our analysis is based on a very large number of measurements of width and of depth. This has allowed us to significantly reduce errors relating to the location of transverse profiles, while in other studies of the impacts of dams relatively few transverse profiles were compared.

The second type of error (relating to determining channel width and depth at the bankfull stage) did not pose great problems with regard to the Warche. The channel is very well-defined in its floodplain. Consequently, it was not difficult to determine the width and depth at the bankfull stage, whether on site or with the use of maps. This has allowed measurements taken at different times to be easily compared. Therefore, we consider this error to be negligible and without any significant influence on the results.

In light of these considerations, the considerable increase observed in the width of the Warche downstream from the Butgenbach dam cannot be attributed to errors resulting from the comparison of measurements taken from the topographic maps and those taken directly on site. The widening of river channels downstream from dams has already been observed by many authors. As a general rule it results from an increase of discharge but sometimes from the absence of a change of discharge after the dam has been built. This has been shown in the general schemas of river adjustment proposed by Schumm (1977), Xu (1990) and Brandt (2000). These models have been supported by field observations (Kellerhals *et al.*, 1979; Petts and Pratts, 1983; Church, 1995). Taking the intensity of floods into account, Kellerhals *et al.* (1979) observed a widening of the river Kemano (Canada) after the tripling of its mean annual discharge. It is necessary to determine whether widening is a result of river diversion or a result of the dam. Petts and Pratts (1983) observed the widening of the river Ter (Great Britain) as a result of an increase of small floods. In the case of the Warche, even if the increase of these minor floods may partly explain the widening of the river it cannot account for the amplitude of this widening, in banks relatively resistant to erosion and consisting of cohesive material (compacted silts). In fact, the width of the river has doubled in 45 years. The doubling of width mainly results from the process of islet formation and erosion, as detailed earlier. This process is favoured by a reduction in suspended load. Two factors are responsible for this reduction: the Butgenbach dam and the change in land-use of the catchment, following the substitution of forests and prairies for agriculture. The change in land-use explains the widening of the channel of the Warche upstream from the Butgenbach dam (Assani *et al.*, in press). It also explains the poor supply of suspended sediment of the tributaries of the Warche downstream from the Bugtenbach dam.

It ensues that the considerable widening of the channel of the Warche downstream from the Butgenbach dam is firstly due to floods greater than the bankfull discharge which led to the formation and erosion of islets. Widening occurs despite the fact that discharges are less frequent and of shorter duration. This widening, therefore, does not result from an increase of discharge frequency as indicated in the three models of adjustment mentioned earlier. Nonetheless, we should point out that floods less than the bankfull discharge, of which the frequency has been considerably increased, provide a secondary contribution to widening the channel, by eroding the islets in winter when they are devoid of vegetation. Besides, the early formation of residual paving has favoured bank erosion and has contributed (although only slightly) to the widening of the channel. This is indicated by the bars downstream from the dam. These bars are supplied with material which comes from erosion of the river banks. The proliferation of bars (associated with the erosion of river banks after incision has ceased and following the formation of residual paving) has been described by Xu (1996) downstream from the reservoir constructed on the river Hanjiang in China (Xu, 1997).

The absence of longitudinal variation of width below the dam shows that it has influenced the whole 7 km reach and not only the sector just below the dam, as observed by Petts (1984). Wolman (cited in Brandt, 2000) observed in nine American rivers that the length of the sector affected by degradation varied greatly from one river to the next, with values from 0 to 70 times the width of the river. The absence of longitudinal variation in the Warche is the result of frequent releases which are able to transport the finer particles, which formed part of the bed. This also causes the disappearance of the riffles where most of the bedload would normally have stopped. The releases facilitate the propagation of the bedload further downstream and thus have an effect on the whole section.

Meanwhile, the contribution of the tributaries of the Warche in liquid and solid discharge remains negligible due to their small size. They do not affect the changes imposed by the dam, as has been observed by a number of authors at selected dams (Benn and Erskine, 1994; Brandt, 2000). Widening continues for 60 years after the construction of the dam by erosion of islets. However, with regard to depth, incision has ceased (probably quite soon after the construction of the dam) due to the fact that the bedrock has been reached and an armoured bed has developed. Finally, enhanced incision downstream from the dam, as observed by Morisawa (1985), has not taken place in the case of the Warche.

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