probably close to the virgin pre-drilling rock temperature was inverted by Clauser et al. (1997). The reconstructed amplitude of the glacial/interglacial warming is nearly 10 K. Another high value, although for much higher latitude of 72.6 °N, was obtained by a Monte Carlo inversion of the 3000m deep temperature profile measured through the Greenland Ice Core Project borehole (Dahl-Jensen et al., 1998). It suggested amplitude of the postglacial warming 23 K.

Although the study showed that the resolving power of the inversion procedure on the time scale of the last glacial/interglacial transition is limited and very likely in the individual cases biased due to the various factors, it seems to be evident that there is the climatic signal of this event in the present subsurface temperature field of central Europe and that the ground surface temperature contrast between the glacial minimum and postglacial optimum was of the order of 10 K.

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Climate Impact on River Processes, Landforms and Deposits in the Last Glacial

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ABSTRACT. Soil cohesion and peak discharges are the main climate-derived factors that determine river processes. They are related to vegetation cover and permafrost conditions. Climatic effects on Quaternary river systems are time-scale dependent. The response time of river processes to climatic changes may restrict their sensitivity to adapt to short climatic oscillations.

KEY WORDS: Quaternary rivers, fluvial geomorphology, climate impact, periglacial rivers.

The effect of time scale

Fluvial morphological and sedimentological development works simultaneously at the different scales, superposing the smaller scaled effects on the larger ones (Schumm, 1975). This development results from various intrinsic dynamics and extrinsic forces. It has been shown that the response of the fluvial system to changing climatic conditions is dependent on the considered time scale (Vandenberghe, 1995).

• *glacial/interglacial level (10^5–10^6 years)*

The traditional concepts of climatically determined morphologic and sedimentological phenomena are born from that climatic cyclicity: terrace staircases, plan form changes and grain-size alternations of the fluvial deposits. Indications for glacial climatic conditions were indeed found at many occasions in the coarse terrace deposits. The erosional gaps are not so easy to characterize, but apparently there is no other place for them than in the interglacials.

• *intra-glacial cycles (10^3–10^5 years)*

The coarse terrace deposits, attributed to glacial stages (with a duration of ten thousands years), are often only a few meters thick (or less) and could be deposited in very short times. Also the grain size of cold deposits may be very different due to considerable climatic variation within a glacial period (van Huissteden, 1990; van Huissteden and Vandenberghe, 1988) and also to intrinsic evolution (e.g. Kasse et al., 1995). In addition interglacials should not explicitly be identified as erosional periods: many Holocene rivers are very calm and there even seems to be some aggradation in the valley floors instead of erosion.

All these facts led to the development of a more detailed conceptual model of fluvial development (Vandenberghe, 1993, 1995). It identifies especially the climatic transitions as phases of morphological instability and thus erosion. In the glacial periods there was a relatively large amount of sediment supply to the rivers, but most of it could be transported by the periodically high transport capacities of these rivers.

• *short-term warm oscillations in glacial periods (10^{2-3} years)*
Since climatic oscillations as recorded in marine and ice cores appear to be of quite large amplitude and also indications on land point in similar direction (e.g. Coope et al., 1997; Kasse et al., 1995) it may be wondered what their effects could be on fluvial evolution (see below).

The intermediaries of climate impact on river dynamics

a. General

Sediment supply is influenced greatly by the soil cohesion. In the case of unconsolidated sediment, the cohesion is - to a large extent - a function of the vegetation cover (e.g. Millar, 2000), but in periglacial conditions it may also be enhanced by the frozen state of the soil. The available energy is related to the discharge. The amplitude of the peak discharge is most important. In periglacial conditions the peak discharge is determined especially by the snow melt in spring and the absence or presence of a frozen subsoil.

b. Example to illustrate the effect of vegetation

One of the best documented examples to illustrate the contribution of vegetation to the activity of lowland rivers is the fluvial development at the transition from the last glacial Pleniglacial to the Lateglacial interstadial at c. 14.7 cal ka. At the end of the Pleniglacial there was an almost bare surface; it was colonized progressively by vegetation from the beginning of the Lateglacial onward. At the same time precipitation increased considerably, but continued to be mainly produced as snow in winter. The water that resulted from the rapid melt of the thick snow cover flowed over still frozen soil, and thus could not infiltrate. The sediment load of the rivers decreased drastically, while peak discharges were high in spring. The morphologic effects were river down-cutting and the change from a braided to a meandering plan form.

c. Examples to illustrate the effect of permafrost

It appeared that the Weichselian Middle Pleniglacial rivers in The Netherlands did not show the braided pattern which was supposed to be typical for rivers during glacial times (van Huissteden et al., 1986; van Huissteden and Vandenberghe, 1988). That braided pattern was only found in the Early and Late Pleniglacial, while the middle Pleniglacial rivers were described as meandering, and later on as anastomosing (van Huissteden, 1990; Mol, 1997). This subdivision was largely concordant with climate: permafrost conditions in the Early and Late Pleniglacial but only sporadic or discontinuous permafrost in the Middle Pleniglacial.

In contrast to The Netherlands, the fluvial successions of the later part of the Middle Pleniglacial in eastern Germany (< 40 ka) show all characteristics of a braided river (Kasse, in prep.). These deposits contain large cryoturbations, occasionally associated with ice-wedge casts, pointing to continuous permafrost. Thus a major break in the river characteristics occurred around 40 ka, parallel with a change in climatic conditions leading to permafrost development. It may be attributed to the crossing of a threshold in the stream-power/bedload rate as a result of higher peak runoff and higher bank cohesion.

The effects of small climatic fluctuations

Short but rapid climatic oscillations have been detected in marine and ice records of the last glacial. Also in terrestrial records it was derived that the Middle Pleniglacial climate was more variable than previously thought. The most pronounced cold interval in The Netherlands is the Hasselo Stadial (van Huissteden, 1990) at ca. 41–38.5 ka, followed by the warm Hengelo Interstadial (Zagwijn, 1974). The pregnant question is to know if these short episodes are reflected in the river morphology. Short erosion-deposition events coinciding with short climatic cold and warm alternations have been reported by van Huissteden (1990) and Huisink (1999). However, it is not easy to distinguish such fluvial events from events that reflect merely the intrinsic evolution in a river system. The overall sedimentation pattern (fine, organic deposits in an anabranching pattern) did not change much (e.g. Kasse et al., 1995). This is in contrast to the coarse sediments in braided patterns during the Early and Late Pleniglacial periods that were not much colder than the Hasselo Stadial (Huijzer and Vandenberghe, 1998).

We suppose that the reason for this discrepancy in river behavior is the short duration of these cold or warm episodes. It could be shown that an adaptation in river plan form could take several hundreds of years (Vandenberghe et al., 1994). Such a delayed response, which is due to the internal river dynamics, does not allow rivers to respond to climatic oscillations that have a duration in the same range as the delay times.

Conclusions

- thresholds of climate, vegetation and soil conditions play an important role;
- there is a striking difference in river behavior and characteristics in regions with deep seasonal frost, in comparison with regions with continuous permafrost.
- short climatic fluctuations have left in most cases no imprint in the fluvial sediment succession.

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Change in the Frequency of Extreme Events as the Indicator of Climatic Change in the Holocene

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ABSTRACT. The transformation of natural systems in the Holocene by climatic factors is realised by the change in the type of extreme events or by change in their frequency or by both. These changes are exemplified by the transition from the Younger Dryas to the Preboreal and by wetter phases of higher flood frequency and reactivation of slope processes in central Europe.

KEY WORDS: climatic change, phases of high frequency of extreme events, fluvial systems.

The transformation of fluvial systems, both valley floors and slope sectors is realised during extreme events, when the equilibrium is disturbed and tresholds iniciating various processes are passed. Among those events are heavy downpours, continuous rains, rainy seasons, rapid snowmelts combined with heavy rains etc. (Starkel, 1996). Heavy downpours over restricted areas cause extensive slope wash, gullying, earth and debris flows and local floods. Continuous rains of regional scale create various mass movements, piping and flooding in larger catchments. Rainy seasons reactivate deep landslides. Rapid snowmelts depending on the freezing of the ground and rainy components may lead to heavy soil erosion (with shallow earthflow) and ice-jam floods.

Every climatic change means either a change in the type of events, change in their frequency or both. Change in type is exemplified by the shift from snow-melt floods with ice-jams to rainy floods. Change in the frequency could run separate or parallel with the change of type in events.

The case of parallel change of the floods type and frequency may be caused by rapid cooling or warming. At the transition from the Younger Dryas to the Preboreal the Gościąż Lake (Ralska-Jasiewiczowa et al., 1998) and several other localities with annually laminated sediments recorded during several decades a rise of the mean annual temperature of the order of 3–5 °C. Instead of frequent snow-melt floods during the Younger Dryas there followed the Preboreal with less frequent rainy floods. The sediment load was reduced drastically due to expansion of forest communities in the Central Europe. Farther to the North-East in the boreal forest zone the snow-melt floods are still dominating, but their frequency and geomorphic role substancially decreased.

Therefore in dozens of middle reaching central European river valleys are observed rapid changes from braided river channels or large meander to small meanders (Fig. 1), indicating the decline of bankfull discharges by 5 times and more (Szumański, 1983; Starkel, 1990; Rotnicki, 1991; Starkel et al., 1996). This coincides with the decline of sediment load and formation of extensive back-swamps instead of coarse-grained bars and overbank deposits.

The other case of main shift only in the frequency of extremes is represented by several wetter phases during the Holocene characterised by much higher flood frequency (Starkel, 1983, 1998). These floods are responsible not only for a higher deposition rate, for intensive lateral erosion and accretion, but also for the straightening and widening of channels with braiding tendency and avulsions (Fig. 2). During the Holocene in the central Europe there were recognised several such phases; 8.5–7.8, 6.6–6.0, 5.5–4.9, 4.5–4.2, 3.5–3.0, 2.8–2.7, 2.2–1.8 ka BP, 10th–11th century and the Little Ice Age (Starkel et al., 1996).

But we observe that the trend towards differed downcutting or aggradation during particular phases. During the older ones prevailed the downcutting tendency, since Roman or mediaeval time it changed to aggradation due to deforestation and extensive agriculture. The turn to more stable river regime with less frequent floods caused again the stabilisation of river channels and developing of free meanders.

In the case of the Atlantic-Subboreal transition towards a slightly cooler/wetter climate in the global scale, this change in the temperate zone of Europe is accompanied by two distinct phases with higher frequency of extreme events ca 5.5–4.9 and 4.5–4.2 ka BP (Kalicki, 1991; Starkel et al., 1996).

The first of such wetter phases during the Holocene is especially well recorded at Podgrodzie site, where in the small alluvial fan ca 6 meters thick deposited between 8.4–7.8 ka BP the proluvial sands and silts are representing at least 100 heavy rains (Starkel, 1984; Czyżowska, 1997). This indicates that during this phase, both heavy downpours and continuous rains were frequent.

The last cooler phase known as the Little Ice Age is well expressed in deposits and forms due to the higher rate of processes connected with an accelerated runoff and sediment load after extensive deforestation.