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ECOLOGICAL EFFECTS OF RE-MEANDERING LOWLAND STREAMS AND USE OF RESTORATION IN RIVER BASIN MANAGEMENT PLANS: EXPERIENCES FROM DANISH CASE STUDIES

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ABSTRACT

River restoration was authorized in Denmark with the Watercourse Act from 1982. Since then, more than 60 large re-meandering projects have been carried out but only a few have included monitoring the ecological effects. In this paper we have analysed the ecological benefits of three types of re-meandering projects covering small headwater streams (1st and 2nd order), medium-sized streams (3rd and 4th order) and large streams (5th and 6th order). All three re-meandering projects included pre-monitoring and post-monitoring of macrophytes and macroinvertebrates; the longest monitoring period lasted for 19 years after re-meandering. We found large differences in the recovery of macoinvertebrate and macrophyte diversity in the three different stream types. The 1st order Gudenå stream had a poorer ecological quality two years after re-meandering work had finished, the 3rd order river Gelså had recovered after two years, and the 6th order river Skjern had already regained or even improved the ecological quality after one year. The results suggest that the start of post-monitoring programmes should be planned with due attention to the stream order and upstream colonization potential. The nineteen years of post-monitoring in the Gelså case study show that passive restoration by ceasing stream maintenance (weed cutting) can be a restoration measure as effective as active re-meandering of the stream channel. Finally, we have analysed how river restoration can be used as a mitigation measure to improve the hydromorphological and ecological conditions in a Danish river basin when implementing the EU Water Framework Directive. Our case study is the Pilot River Odense catchment where we suggest four new restoration measures to be

implemented for a total of 227 km open stream channels and 236 km culverted streams not supposed to reach good ecological status by 2015.

Key words: river restoration, re-meandering, ecological effects, monitoring, maintenance, Water Framework Directive.

1. INTRODUCTION

European rivers and their riparian areas are used for many purposes and are among those habitats most severely affected by human activities (EEA, 2005 and 2007). In many countries, modification of rivers and their riparian areas has been undertaken for centuries (e.g. EEA, 1995; Phillips, 1995; Sparks, 1995; Kronvang et al., 1998; Bernhardt et al., 2005). Physical degradation has been particularly great over the last two centuries as a result of land drainage, flood plain urbanisation, flood defence and navigation (EEA, 1995). In Denmark, less than 10% of the watercourses and riparian areas are still in a natural physical state (Hansen, 1998). Poor physical conditions often have a negative impact on water quality, e.g. because oxygenation and self-purification are less effective. At the same time, habitats for the flora and fauna will be limited in number and quality if the watercourse lacks physical variability. The consequence has been extensive damage to the river ecosystems with an extensive loss of habitats for wild fauna and flora. As a consequence, the biodiversity of European rivers and floodplains is today significantly reduced compared to that which existed under reference conditions, i.e. with only slight anthropogenic pressures (EEA, 2007).

Since 1982, a large number of stream restoration projects have been undertaken in Denmark with the purpose of: (1) increasing habitat diversity; (2) restoring free passage between stream reaches to ensure the migration of fish and macroinvertebrates; (3) restoring the natural physico-chemical and biological contact between streams and floodplains through e.g. remeandering of formerly straightened stream channels (Hansen, 1996). Active re-meandering of stream channels has been a widely used restoration tool with the aim of immediately bringing back the river morphology to a near natural hydromorphological conditions.

Although re-meandering of straightened reaches is expensive, very few studies have so far documented its hydromorphological and ecological effects (e.g., Friberg et al., 1994; Friberg et al., 1998; Kronvang et al., 1998; Biggs et al., 1998). The purpose of this paper is to describe the short and long term effects of re-meandering projects conducted in different Danish stream types. The hydromorphological and ecological conditions were measured by monitoring different biological indicators (macroinvertebrates, macrophytes and fish). Based on a pilot study in river Odense we also analysed watercourses at risk of not fulfilling the Water Framework

Directive objectives of a good ecological quality, and we suggest solutions such as which restoration methods would be the best choice in the river basin management plan.

2. CASE STUDY SITES

In this study, the focus is on three remeandering projects conducted in each of the three Danish stream types (Type 1 1st and 2nd orders; Type 2 3rd and 4th orders; Type 3 5th and 6th orders), and the Odense Pilot River Basin as a demonstration of how river restoration methods can be used when implementing the EU WFD. The four case study sites are situated in different parts of Denmark (Figure 1). The River Gudenå project was carried out near the source of the river system and is therefore characterised as a Type 1 stream, the river Gelså project is a Type 2 and the River Skjern å re-meandering project was conducted at the lowermost 20 km of the river system, therefore being Type 3. The three re-meandered streams and the streams in the Odense Pilot River Basin are all lowland rivers running in alluvial or moraine sediments. The natural planform of Danish rivers are single channel meandering rivers. Agriculture is the dominant land use in the four studied catchments as in most Danish catchments.

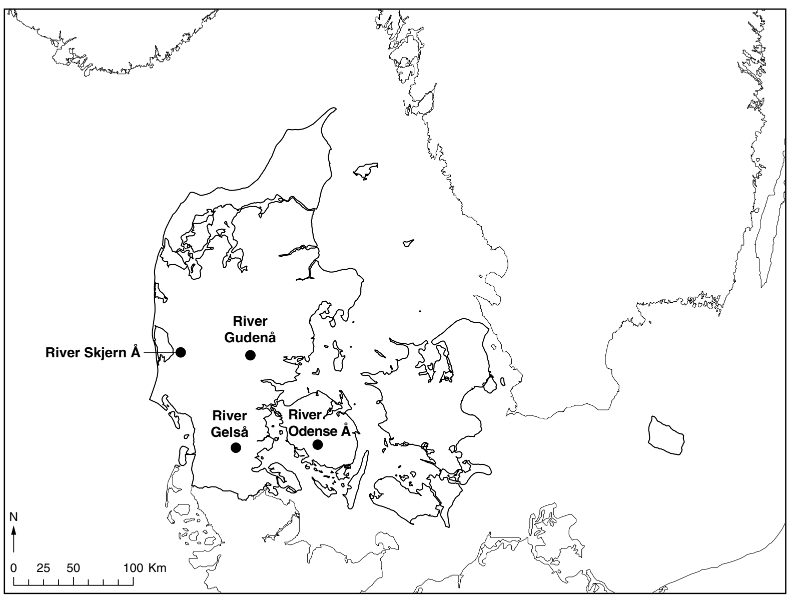

Figure 1 - Location of the four case study sites being the three remeandering projects (Gudenå, Gelså and Skjern å) and the Pilot River Odense.

3. RESULTS

3.1 Ecological effects of re-meandering Type 1 streams: upper River Gudenå

The hydro-morphological conditions changed considerably following remeandering of the upper river Gudenå (Table 1). The width of the channel was designed and created narrower than the channelized reach and the number of meanders increased from 2 to more than 50. Consequently, the length and sinuosity of the river channel were increased.

Macro-invertebrate diversity had not recovered to pre-restoration level after 2 years (Table 2). Furthermore, re-meandering did not increase total species richness of plants, compared to data collected before re-meandering, and total plant cover had not recovered to pre-restoration levels 2 years after re-meandering (Table 2).

Table 1 - River channel characteristics before and after re-meandering of the upper river Gudenå.

River Gudenå	Channel width (m)	Slope (‰)	Length (m)	Number of meanders	Sinuosity	River bed Width (m)	Gravel/ stone coverage (%)
Before	2-5	1.8	2700	2	1.06	1-2.3	0
After	1-41	1.41	32001	>50	1.25	0.30	0

[1]Hansen, 1997

Table 2 - Number of macroinvertebrate taxa, Average Score per Taxon (ASPT) index, number of plant species and total plant cover before and after re-meandering in river Gudenå.

River Gudenå	Before restoration	1 year after	2 years after
Total number of invertebrate taxa	38		25
ASPT	5.4		4.7
Total number of plants species	192	121	167
Total plant cover (%)	38	6	8

3.2 Ecological effects of re-meandering Type 2 streams: River Gelså

The hydromorphological conditions changed considerably following remeandering of the river Gelså (Table 3). The width of the channel was designed and created narrower than the channelized reach and the number of meanders increased from 0 to 16. Consequently, the length was increased by 38% and the sinuosity of the river channel increased from 1.15 to 1.60. The increase in slope following remeandering of river Gelså was due to the demolition of a weir just upstream the project area occurred at the same time as the restoration (Kronvang et al., 1994).

Table 3 - River channel characteristics before and after re-meandering of river Gelså.

River Gelså	Channel width (m)	Slope (‰)	Length (m)	Number of meanders	Sinuosity	River bed Width (m)	Gravel/ stone coverage (%)
Before	9-12	0.81	1300	0	1.15	5-6	47/2
After	4-8	0.86[1]	1800[1]	16	1.60	1.7-5.5[1]	25/16

[1]Kronvang et al., 1994

In River Gelså abundances of brown trout recovered to pre-restoration levels 1-2 years after re-meandering (Table 4); however, the restoration did not result in increased abundance of brown trout in the re-meandered section compared to pre-restoration levels. Furthermore, habitat suitability modelling in river Gelså showed that re-meandering of this stream did not result in increased habitat suitability for brown trout compared to control sites (Fjorback et al., 2002). Similar to abundance of brown trout, macroinvertebrate and plant communities in river Gelså were found to recover relatively fast to pre-restoration levels after re-meandering with the number of invertebrate taxa, ASPT value and plant diversity reaching pre-restoration levels after 2 years and showing tendencies to improve further in the following years (Table 4).

Table 4 - Brown trout abundance, macroinvertebrate taxa, ASPT index, number of plant species, total plant cover before and after re-meandering river Gelså.

	Before[1]	1 year after	2 years after	7 years after	8 years after	13 years after	19 years after
Brown trout density in spring (ind. per 100 m^2)	17.01	3.55	8.99	7.48	9.21	-	8.92
Total number of invertebrate taxa	35	30	45	-	42	-	39
ASPT	5.4	5.3	5.5	-	5.2	-	5.7
Total number of plants species	19	23	30	-	-	28	-
Total plant cover (%)	41	14	47	-	10	-	21

[1]estimate made in June 1989

The total richness and coverage of plant species increased during the first two years following the restoration (Table 4). Species that are not confined to grow within the stream channel i.e. emergent terrestrial species increased more, probably reflecting the increased migration of bank species into the stream during summer. This enhanced contribution of emergent species to the total richness probably relates to the more shallow banks created in the restoration works that facilitate the migration of these species. The abundance of species also changed following restoration. Of particular interest is the appearance of *Potamogeton alpinus*, a species previously widely distributed in Danish streams but that has undergone a marked decline due to a more intensified land use. The appearance of this species highly sensitive to disturbance is probably due to changes in the stream maintenance practice (Pedersen, Baattrup-Pedersen & Madsen 2006). Thus, prior to restoration, the vegetation within the stream channel was cut regularly (more than once per year), whereas after restoration the vegetation was left undisturbed.

Combined habitat and ecological effect monitoring in the River Gelså was not only carried out at the remeandered reach but also at an upstream control site (Friberg et al., 1999). River maintenance work (weed cutting and excavation) ceased at both control and restored reaches following re-meandering in 1989. The hydromorphological conditions developed in an almost similar way at the control and remeandered reaches 19 years after completion of the restoration work. Main differences in substrate conditions between the upstream control and downstream restored reaches showed that less gravel and more stones were present at the latter and that no major differences occurred between the two years of mapping (Figure 2). The density of brown trout was on average higher at the two upstream control reaches (11.3 trout per 100 m^2) than at the five restored reaches (8.9 trout per 100 m^2). On the other hand, the ASPT index for macroinvertebrates was on average higher at the active restored reach (5.7) than at the control reach (5.1). The reason for the difference was only due to stone-dwelling species linked to the much higher coverage of stones in the active restored channel (Figure 2). The diversity of macrophytes was almost the same at both the remeandered and the control reaches.

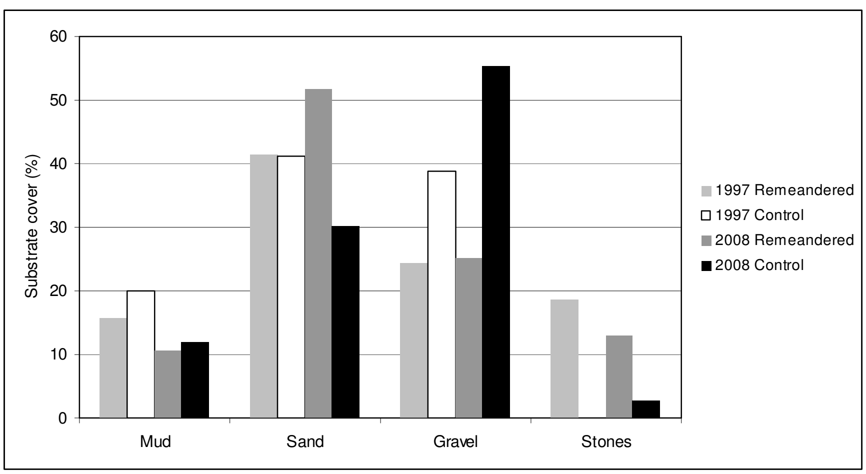

Figure 2 - Substratum conditions on two upstream control reaches and five re-meandered reaches in 1997 and 2008 in river Gelså.

3.3 Ecological effects of re-meandering Type 3 rivers: the River Skjern

The hydro-morphological conditions changed considerably following remeandering of the River Skjern Å (Table 5). The width of the channel was narrowed considerably (31%) and the number of meanders was increased from 8 to more than 45. Consequently, the length was increased by 37% and the sinuosity of the river channel increased from 1.04 to 1.23. No changes in channel slope occurred along the re-meandered River Skjern as a weir at the upstream part of the restored reach was demolished (Pedersen et al., 2007b).

In River Skjern macroinvertebrates rapidly colonized the three studied sections of the 26 km new meandered reach. The remeandering of the old 19 km river channel lasted 3 years starting downstream with section 3 the first year, section 2 the second year and ending the last year with section 1. Post-restoration monitoring was conducted in the new meandering channel after 3 years. The results of e macroinvertebrates monitoring therefore reflect different colonization times for the three sections surveyed (Table 6). However, macroinvertebrate diversity had exceeded pre-restoration levels at section 1 after one year and at section 2 and 3, respectively, 2 and 3 years after restoration (Table 6). ASPT values were nearly the same following restoration at section 1 after one year and section 3 after three years, whereas it was lower at section 2 two years after restoration work was completed (Table 6). Two rare macroinvertebrate species (the caddisfly *Glossosoma boltoni* and the stonefly *Isopetena serricornis*) never recorded in the channelized reach of the River Skjern were found during post-monitoring of the re-meandered channel. *Glossosoma boltoni* is known from stony riffles on unregulated upstream parts of the River Skjern, whereas I*sopetena serricornis* requires stable sandy substrate as preferred habitat. The diversity of plant communities also developed fast following re-meandering in all reaches, however, total plant cover was found to be slightly lower three years after restoration (Table 6).

Table 5 - River channel characteristics before and after re-meandering of the river Skjern.

River Skjern	Width (m)	Slope (‰)	Length (m)	Number of meanders	Sinuosity	River bed Width (m)	Gravel/stone coverage (%)
Before	49	0.23	19000	8	1.04	35-45	8
After	341	Not affected[1]	260001	>45	1.23	25-35	12

[1]Pedersen et al., 2007

Table 6 - Number of macroinvertebrate taxa, the ASPT index, number of plant species and total plant cover before and after re-meandering in river Skjern.

	Before	1 year after	2 years after	3 years after
Total number of invertebrate taxa				
Section 1	40	44		
Section 2	44		50	
Section 3	41			55
ASPT				
Section 1	6.0	6.1		
Section 2	6.5		6.0	
Section 3	6.1			6.1
Number of plants species per m^2	0.7	-	-	0.6
Total plant cover (%)	34	-	-	24

3.4 Case study Odense Pilot River Basin: use of restoration measures when implementing EU WFD

Odense Pilot River Basin covers an area of approx. 1,050 km^2, corresponding to approx. 2.5% of the Danish land area. There are just over 1,000 km of watercourse in the river basin, including the largest river on Funen, the River Odense, which is about 60 km long and drains a catchment of 625 km^2. Clayey sand (46%) and sandy clay (46%) are the dominant soil types in the catchment and land use is dominated by agriculture (Table 1). Madsen et al. (2007) give a characterization of the different stream types and the length of streams being at risk of not fulfilling the objective of a good ecological quality by 2015 under the EU WFD (Table 7). 53% of the open natural stream channels are at risk of not fulfilling the objective of a good ecological quality by 2015 and this is of course also the case for the entire length of the culverted stream channels (Table 7). The major reasons for this rather poor ecological status of the streams are the different pressures caused mainly by a poor hydromorphological state (Table 8). Thus, approx. 80% of the stream channels are at risk due to direct pressures on biota from obstructions, and another 86% are at risk due to morphological pressures such as channelization and poor physical habitat conditions.

Table 7 - River Odense Catchment divided into natural streams of different types (sizes. Length of natural stream channels where improvements in hydromorphological conditions are needed is estimated (from Madsen et al., 2007).

Stream channels	Type 1 streams (1-2 order)	Type 2 streams (3-4 order)	Type 3 streams (> 4th order)	Artificial watercourses	Total
Total stream length (km)	662	216	53	84	1015
Length of open stream channels (km)	426	216	53	67	762
Open stream channels at risk in 2015 (km)	339	156	39	-	534
Need for improvement of hydromorphological conditions (km)	155	54	18	-	227
Length of culverted stream channels (km)	236	0	0	17	253
Need for improvement of hydromorphological conditions (km)	236	0	0	-	236

Table 8 - Assessment of the pressures on the streams in the Odense Pilot River Basin being at risk of not fulfilling the EU Water Framework Directive of a good ecological status in 2015 (adopted from County of Funen, 2006).

Direct pressures on biota from obstructions, etc.	Morphological pressures.	Hydrological pressures from water abstraction	Hazardous substances	Organic and nutrient pollution
80 %	86 %	1.1 %	4.3 %	41 %

To obtain a good ecological quality in all natural streams in the Odense Pilot River Basin by 2015 the river basin managers will need to adopt mitigation measures that can improve the hydromorphological state of the stream channels at risk. Introduction of a suite of restoration methods will be an obvious choice for the river basin manager. Madsen et al. (2007) present a suite of measures; however, based on our experience from previous Danish restoration projects, we suggest the following four main restoration methods to be applied in the river basin:

R-I: Securing free passage by removal of all obstacles such as weirs, or introduction of bypasses.

R-II: Hard active restoration through re-opening and re-meandering of culverted stream reaches.

R-III: Soft active restoration through ceased stream maintenance in Type 1 streams and allowing for a 2x10 m uncultivated ‘green’ corridor with excavation of a wide double profile if the channel is too deeply incised with steep unstable banks as compared to reference morphological dimensions in Danish streams (Mernild, 2001).

R-IV: Passive restoration through ceased stream maintenance in Type 2 and 3 streams together with improvements in the physical habitat conditions by reinstating gravel, stones and wood in the regulated channel.

Our suggestions on how to implement the four different mitigation measures in the in the Odense Pilot River Basin are shown in Table 9.

Table 9 - Suggestions on how to improve the hydromorphological conditions in the River Odense Catchment, in order to achieve a good ecological status by 2015 through the implementation of four different restoration methods.

	Type 1 (1st -2nd order)	Type 2 (3rd -4th order)	Type 3 (> 4th order)
R-I: Securing free passage (estimated number of barriers)	175	45	0
R-II: Hard active restoration through re-opening and re-meandering of culverted streams (km).	236	0	0
R-III: Soft active restoration (km)	155	0	0
R-IV: Passive restoration – ceased river maintenance (km)	0	54	18

4. DISCUSSION

The three cases of remeandering presented in this study represent some of the most intensively monitored restoration projects in Denmark. Based on the results from this monitoring and evaluations from additional project, it is possible to draw some general conclusions concerning the ecological effects of remeandering lowland streams.

Two years after re-meandering the headwaters of river Gudenå (Type 1: 1st order stream) had not recovered to the ecological state present priori to the restoration (Table 2), probably reflecting the poor recolonization possibilities due to the limited extent of upstream areas and therefore recolonization sources. Aquatic plant dispersion is mainly dependent on downstream transport of either whole plants, shoot fragments or other vegetative organs (Barrat-Segretain and Amoros, 1996). Similarly, recolonization of macroinvertebrates is also partly dependent on potential upstream sources, e.g. through downstream drift of individuals (Matthaei et al., 1997). Furthermore, the recolonization of macroinvertebrates in river Gudenå might have been further delayed because of the low plant cover. Being of paramount importance for the structure and function of lowland stream ecosystems, macrophytes affect the recolonization rate of other stream organisms, including macroinvertebrates (e.g. Sand-Jensen, 1995). Following future restorations in headwater streams, active interventions to assist recolonization should therefore be considered. The river Gudenå is the only case where monitoring data have been published for a Danish type 1 stream and general conclusions should therefore not be drawn. However, evaluations of headwater disturbances (including restorations) in other parts of the world have also highlighted the limited recolonization potential for plants and macroinvertebrates in headwater streams (Whiles and Wallace, 1995; Milner, 1996; Laasonen et al., 1998) and the recommendations may therefore still apply.

In contrast to the restoration of the headwaters in river Gudenå, the biota in river Gelså (Type 2: 3-4th order stream) was only affected on a short-term by the disturbance caused by the re-meandering works (Table 4). Two years following re-meandering of this medium sized stream, the biota had almost completely recovered or even improved, reflecting the generally high recovery potential of stream ecosystems with recolonization sources located upstream (Matthaei et al., 1997). Post-restoration monitoring in the three sections of the river Skjern (Type 3: 5-6th order stream) corroborates these findings as already one year after restoration work was finished, the macroinvertebrate community had recovered at section 1, i.e. the upstream-most (Table 6). These results agree with results from other evaluations of remeandering of relatively large streams in Denmark (Biggs et al., 1998; Kristensen, 2004; Sode, 2005). Recolonization of the remeandered river Skjern by the rare caddisfly *Glossosoma boltoni* and the rare stonefly *Isopetena serricornis,* two macroinvertebrate species never found in the channelized reach of the river Skjern, is also an indicator of the rapid recovery of a re-meandered reach to a more natural state.

Long-term monitoring results from the river Gelså showed that still after 19 years, the diversity of macrophytes and macroinvertebrates is developing towards a more diverse and natural species composition. Moreover, a comparison of the biota on upstream control reaches and the re-meandered reaches revealed that ceasing river maintenance (weed cutting) also had a positive effect on the ecological conditions measured such as brown trout density, number of macrophyte species and number of macroinvertebrates. However, the latter could be ascribed to the higher abundance of introduced larger stones on the restored as opposed to the control reaches, thereby indicating that passive restoration through ceased river maintenance together with the addition of gravel, stones and wood would in many cases be a cost-effective restoration measure. The occurrence of long-term changes in community structure may take place after restoration measures is confirmed by a ten year study in another Danish Type 2 stream (Sode, 2005).

Comparison of macroinvertebrate communities among seven re-meandered and seven naturally meandering streams showed that the re-meandered streams had communities similar to the naturally meandering ones (Kristensen, 2004). This suggests that re-meandering in relatively large streams has the potential to restore macroinvertebrate communities to a more natural state in conjunction with rapid recolonization. The results from

Kristensen (2004) were, however, not a clean effect of re-meandering as maintenance in the streams (weed cutting, dredging) was reduced or ceased at the same time and therefore further improved the communities.

In fact, an earlier study of river Gelså showed that passive restoration of channelized rivers simply by ceasing river maintenance work (dredging and weed cutting) can improve the diversity of macroinvertebrates to a higher level than active restoration through remeandering (Friberg et al., 1998). Another study of 10 re-meandered Danish streams showed that f change in maintenance practises and reduction of the maintenance frequency were important factors in the development of natural macrophyte communities (Pedersen et al., 2006). This study also highlighted that shallow and wide banks improved the connection between the river and the surrounding valley promoting the development of diverse plant communities (Pedersen et al., 2006). When combined, these results therefore suggest that macroinvertebrate and plant communities can recover and improve after re-meandering, provided that stream maintenance is minimised and that the stream banks are reprofiled with a lower bank angle to improve the lateral connectivity between the stream and its valley.

Our results from the three remeandering case studies show that post-restoration monitoring of restoration projects should wait for recolonization of macroinvertebrates and macrophytes to have a reasonable chance to take place (Figure 3). Post-restoration monitoring should therefore not take place before 2-3 years after restoring 1-2nd order streams (like the headwaters of river Gudenå), and should also be avoided during the first year following remeandering of 3-4th order streams (like the river Gelså) in order to avoid false results and save resources for longer term monitoring. Only in 5-6th order streams with a high upstream colonization potential post-restoration monitoring may be conducted with reasonable results one year after completion of the restoration work. However, it should still be kept in mind that significant changes may occur over several years (e.g. Sode, 2005).

Figure 3 - Possible development in the ecological diversity following remeandering in different types of streams (stream orders).

5. CONCLUSIONS AND RECOMMENDATIONS

The ecological monitoring results from some of the best surveyed Danish case studies covering three existing stream types according to the EU Water Framework Directive (WFD) have enabled us to propose a concept for the recovery in biota following active re-meandering in different stream orders. The following concept should be taken into consideration when planning post-monitoring strategies of river restoration projects:

Recolonization of biota in re-meandered river channels can be very fast in > 4th order streams having an upstream colonization potential as it was the case of river Skjern where the macroinvertebrate community recovered within one year.

Recolonization of biota in small 1st and 2nd order headwater streams can take several years as it was the case of the upper river Gudenå case study, where macrophyte and macroinvertebrate diversity were lower than prior to remeandering two years after restoration work had been accomplished.

Recolonization in the medium-sized 3rd order River Gelså took place during the first two years but the ecology seems to steadily improve during the 19 years of post-monitoring, coupled mainly to a development in the plant community towards more disturbance-sensitive submersed species following ceased stream maintenance.

When planning post-restoration monitoring, the results from the three Danish case studies show that river managers should avoid post-monitoring during the first 2-3 years in 1st and 2nd order streams or in streams with a low upstream recolonization potential. In larger streams post-monitoring should be avoided during the first year to avoid false ecological signals.

Our post-monitoring results from the River Gelså shows that ceased river maintenance (stopping weed cutting and dredging) is more cost-effective as a passive restoration measure than active re-meandering especially when combined with the addition of gravel, stones and wood in the river channel.

We suggest a new restoration measure to be adopted along existing channelized and deeply incised 1st and 2nd order stream channels, which include establishment of a 'green corridor' allowing excavation of the nutrient-rich topsoil in a 10 m buffer zone (establishing a double profile) and at the same time ceasing stream maintenance on the channelized reach.

However, our findings clearly show that there is a need for more studies that can assist us in making assessments of the ecological effects of river restoration projects. We believe that hydromorphological and ecological surveys of larger number of existing re-meandering projects covering gradients in stream orders and restoration ages would be a successful way for describing the recovery process in detail, and at the same time mapping the upstream and downstream colonization potential for individual sites.

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