The Negative Impacts of Sedimentation on Brown Trout (*Salmo trutta*) Natural Recruitment, and the Management of Danish Streams

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Abstract: *Deposition rates of fine sediments into egg baskets situated in simulated brown trout redds were measured during the winter of 2002-2003. The survival of brown trout alevins (fry) were recorded to assess if sedimentation was having a detrimental effect on natural recruitment levels within the stream River Langvad. River Ledreborg an almost pristine stretch of stream was used as the control. Both streams are situated in the County of Roskilde, Denmark and are representative of many of the small streams situated on the island of Zealand, Denmark. Sedimentation was found to be having an effect on the natural recruitment levels in River Langvad as no survival of alevins was recorded. A combination of factors was more than likely to have led to such a result. More surprising was the finding of high sedimentation in the River Ledreborg and as a result of this sedimentation; low natural recruitment levels were recorded. Management measures for the two streams are proposed.*

Keywords: Sedimentation, Brown trout, Natural recruitment, Fish habitat, Anthropogenic impacts, Danish streams, Management issues

1. Introduction

The presence of sediment is one of the most obvious characteristics of small streams. Sediment has several forms and several sources, but of greatest concern in streams are the fine inorganic particles (fines <2mm) that either flow with the current (causing turbidity) or that are deposited on the streambed (causing loss of benthic productivity and fish habitat). Such sediment is widespread and pervasive; occurring to some extent in all streams (Meehan 1991, Waters 1995). Most natural sediment inputs are very small and can be incorporated by stream processes into non-destructive forms and quantities. It is excessive sediment, generated as anthropogenic waste, which often overwhelms the assimilative capacity of a stream and damages its biological components (Cairns 1977).

Of all the aspects of sediment pollution the relationship between sediment and salmonid natural recruitment, has been the subject of greatest concern. Two major reasons for this priority are apparent (Waters 1995). First, salmonids appear as the most favoured freshwater recreational fisheries and hold some commercial value to the fishing industry. Second, salmonids such as brown trout use redds (nests made in gravel) in their reproductive strategy, a design that unfortunately functions as a highly efficient 'sediment trap', with dramatic and often catastrophic effects on eggs and alevins (Crisp 1989). Three specific effects of sediment on salmonid redds have been recognised (Elliot 1994):

1. Filling of interstitial spaces in the redd by depositing sediment, thus reducing or preventing further

flow of water through the redd and the supply of oxygen to the embryos or the alevins.
2. Smothering of embryos and alevins by high concentrations of suspended sediment particles that enter the redd.
3. Entrapment of emerging alevins if an armour of consolidated sediments is deposited on the surface of the redd.
4. Various land-use and management activities can affect salmonid habitats. Although the activities themselves may differ widely, the environmental alterations they produce generally affect fish habitats in similar ways. The effects of increased sedimentation on spawning gravels, for example, will be the same whether the sediment resulted from road construction, logging, mining, or livestock grazing. The same is true for other habitat variables such as water temperature, quantity and distribution of instream cover, channel morphology, and dissolved oxygen concentration. Although the way in which sediment will affect stream ecology is similar, whether it comes from logging or agriculture, the management issues surrounding the mitigation of sediment into the streams can, and is very different in its processes (Salo and Cundy 1987, Meehan 1991, Waters 1995).

2. Case Study: Denmark and its Streams

2.1 Background

Danish streams have been affected by several types of human impact according to the reports of those organisations that manage them (Iversen *et al.* 1991, Miljoeministeriet 1991, Hansen and Madsen 1996). Significant impacts on hydrology and sediment yields, adequately documented for particular areas of the world (Thorne *et al.* 1987, Waters 1995), have probably arisen in Denmark from the conversion of heath to farmland in the 19th and 20th centuries. Field and forest drainage, dams and flow regulation structures, bridges, extractive industries, and deforestation would each have contributed.

The modification of streams for the purpose of agricultural drainage was implicit in early Parliamentary legislation as was stated in the Watercourse Law of 29th July 1846 as well as proceeding watercourse acts. The Watercourse Act of 11th April 1949, with amendments in 1963, 1965, 1969 and 1973, stated that 'drainage shall have priority over any other use'. Uses in conflict with this law required the permission of the Watercourse Tribunal. Natural components of the stream such as accumulated sediment, aquatic vegetation situated on the bed and banks of the stream were considered 'obstructions which impeded drainage' (Andersen 1977).

With a total length of approximately 65 000 km, or about 1.5 km per km^2 land area, streams are important component of the Danish landscape. Slightly more than 50% of the streams (in terms of length) are considered natural in origin; the others originate as ditches and drainage channels. The condition of streams and their associated riparian areas is closely linked to the development of agriculture, which until the late 1950's, was the main contributor to the Danish national income. Today agriculture encompasses 62% of the total landmass, but employs only 5% of the workforce in Denmark (Iversen *et al.* 1993).

2.2 Sedimentation problems in Denmark

Sedimentation problems are widespread in many areas of Denmark and have been reviewed by a number of authors (Græsboell et al 1988, Larsen and Henriksen 1992, Sivebaek and Bangsgaard 1995). The effects are similar to sedimentation effects all over the world especially in relation to macroinvertebrates and fish e.g. salmonids. Even in stretches of sinuous streams with the correct physical and biological parameters for holding a diverse and healthy range of macroinvertebrates or where a section of stream is perfectly suited for spawning of salmonids, problems from sedimentation are still occurring in Denmark. Excess sediment transported from modified, upstream reaches to downstream spawning grounds quickly renders them useless. Larsen and Henriksen (1992) studied six streams on the island of Zealand using brown trout to test for the effects of sedimentation and concluded that sedimentation was a significant problem, especially in the streams where the surrounding land was being used for agriculture. The study concluded that levels above 8% fine sediment (percentage fines) was lethal to the hatching and emerging alevins and that levels of 5 – 6% were reasonable for adequate survival of emerging alevins.

3. Materials and Methods

Two gravel-bed reaches of two small Danish streams were selected for the study, both of which are used for spawning in the autumn and winter by brown trout. The study sites were located within River Langvad and River Ledreborg, both on the island of Zealand, Denmark, approximately 30 km west of the capital Copenhagen within the regional authority of Roskilde (Figure 1). The major differences between the two rivers, is the amount of forested area compared to agricultural area. Much of River Ledreborg is forested (32%) and a large percentage

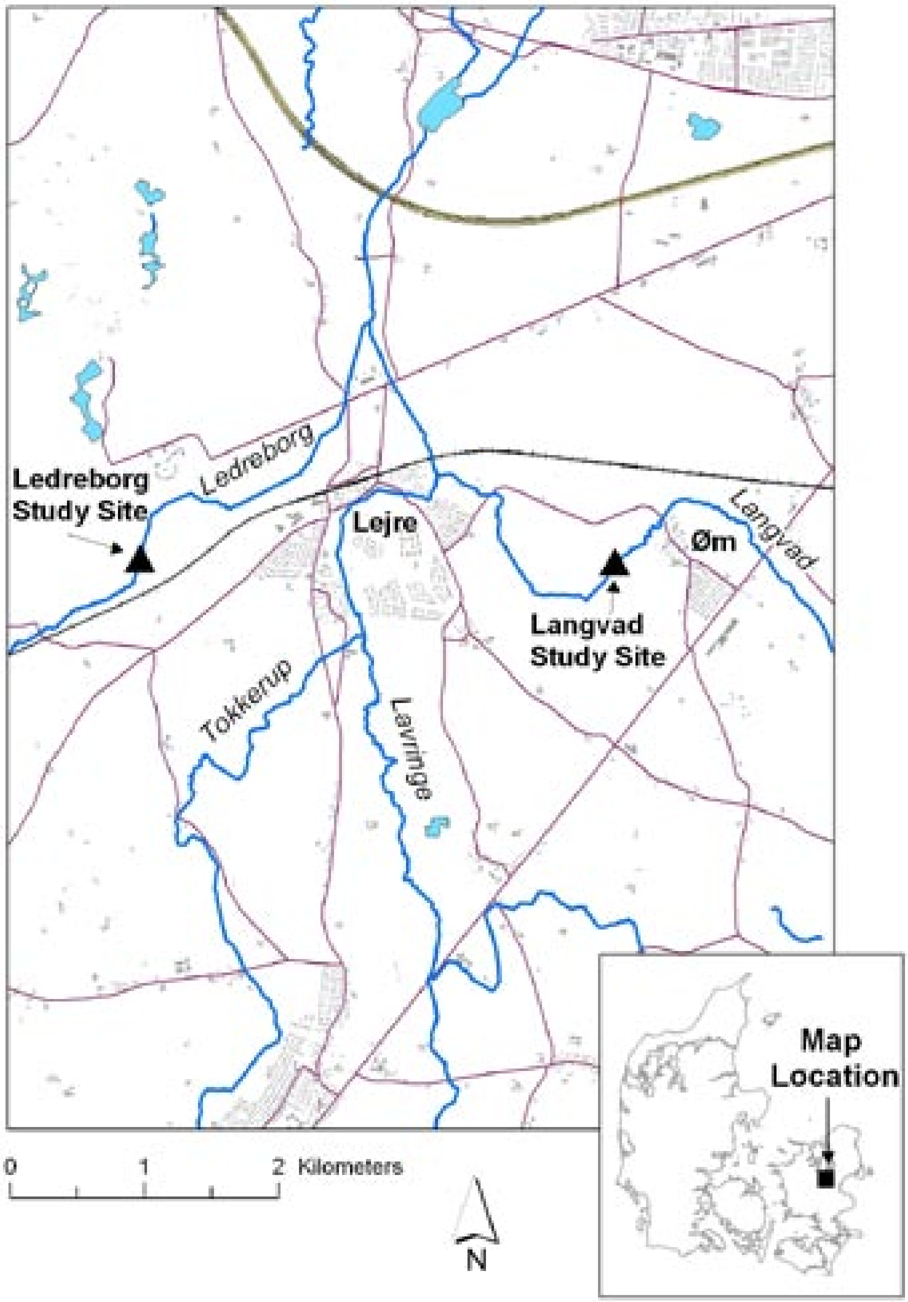

Figure 1. *Map of the River Kornerup catchment and the exact location of both study sites*

is for agricultural use (65%) where River Langvad has very little forest cover (1%) but is mostly made up of agricultural area (82%) (Helmgaard and Rasmussen 1995).

Gravel-filled permeable infiltration baskets, similar to those described by Larsen and Henriksen (1992), Sivebaek and Bangsgaard (1995) were used to monitor the rate of fine sediment deposition (fines) into the spawning gravels of River Langvad and River Ledreborg (Figure 2). Figure 2 shows the basket buried in the simulated redd and the different components of the egg basket. The oxygen pore tubes can also be seen protruding from the baskets edge. Each study site had three treatments approximately 100 m apart and each of these treatments contained two egg baskets buried flush with the stream bed surface in both streams. Treatment selection was within old brown trout redds that were suitable for redd construction but were not yet in use from the natal spawning brown trout. On removal, the protective bag was pulled up to trap all the accumulated fine sediments and survival of alevins recorded by removing the egg sock. Fine sediment was measured back in the laboratory.

4. Results

4.1. Sedimentation

Sedimentation rates varied greatly both within rivers and between the two rivers (Table 1.) Sedimentation rates ranged from 7% to 17.5% in River Langvad (test stream) and in River Ledreborg (control stream) they ranged from 14% to 39% (Table 1.). T-tests (with a different variance) showed that there was a significant difference between the two rivers in relation to percentages of fine sediment. When looking at the Table 1, it is obvious that on average the levels of sediment in River Ledreborg (24.4%) were higher than in River Langvad (12.7). It was not expected that the control stream River Ledreborg would contain more sediment than the test stream

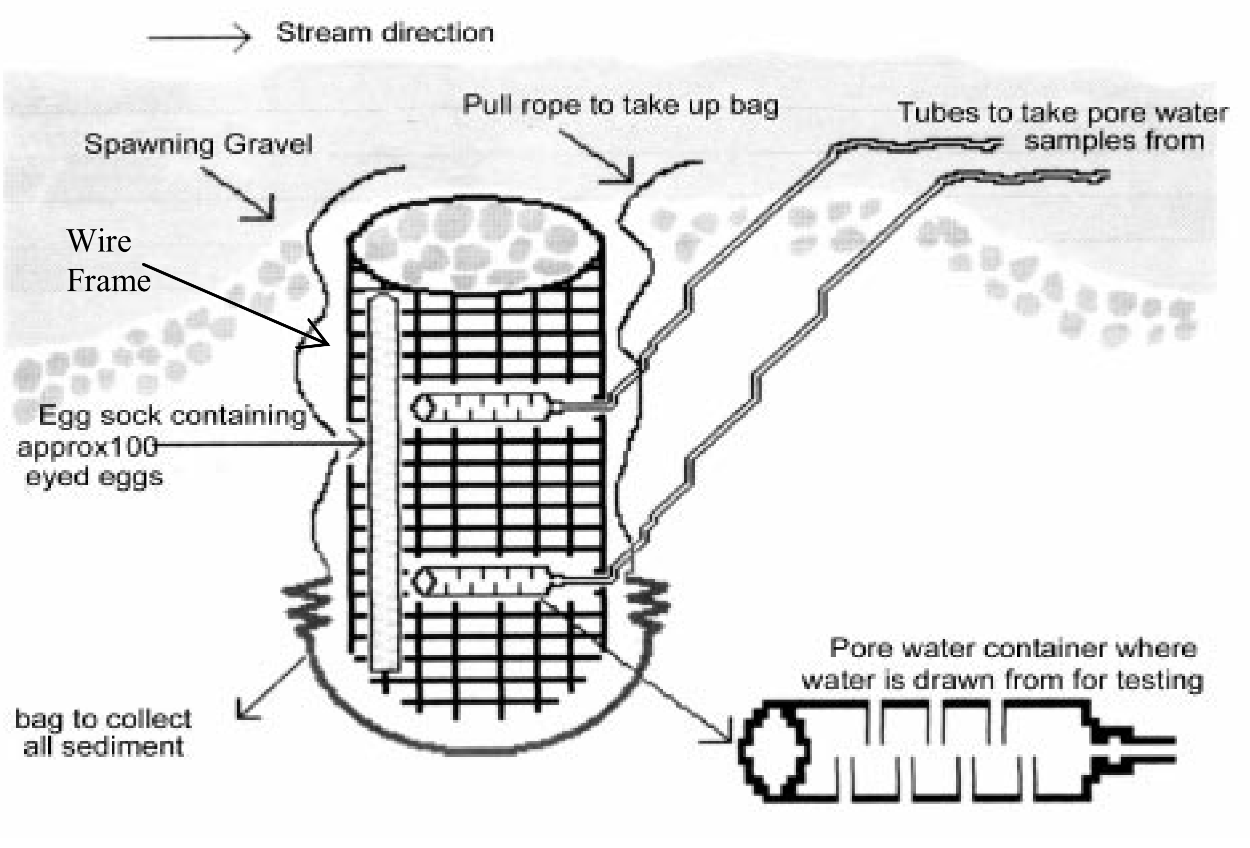

Figure 2. *Diagram of egg basket, and what it would look like when placed in the simulated brown trout redd. (Modified from Nielsen 2003)*

River Langvad. The levels of fine sediment in both rivers were at or above levels, which are proven to be detrimental to developing alevins (i.e. 8%). This would have been a major contributor to no survival being recorded in River Langvad and minimal survival in River Ledreborg.

4.2. Survival Percentage of Alevins

In the River Langvad there was found to be no survival in all replicates.
In River Ledreborg survival percentage ranged from 1% to 12% (Table 1).

4.3. Percentage of Organic Matter (OM)

OM was calculated as a percentage of the fine sediment (<2mm) and in the River Langvad ranged from 2% to 4.8% with an average of 3.32 % (Table 1). In the River Ledreborg it ranged from 1.5% to 5% with an average of 3.0 % (Table 1).

Table 1. Laboratory results summarised into table form. A small explanation is given below of what the different cells are representing

River Langvad - Survival and Sediment data				**River Ledreborg – Survival and Sediment data**			
Replicates	**<2mm % 8% CL**	**Survival %**	**Organic Matter%**	**Replicates**	**<2mm % 8% CL**	**Surviva%l**	**Organic Matter%**
R1	16.8	0	2.4	**R1**	18.4	1.1	5
R2	15.5	0	3	**R2**	14	2.2	3.2
R3	17.5	0	2	**R3**	24	10.0	2.3
R4	7	0	4.5	**R4**	39	13.3	1.8
R5	7	0	4.8	**R5**	35.3	6.7	1.5
				R6	16.1	1.1	4

Replicates: *The number of the replicates situated in the stream*
<2mm %: *Percentage of fine sediment (<2mm) compared to amount of spawning gravel in egg baskets*
CL: *Sedimentation critical limit*
Survival %: *Percentage of alevins that survived compared to the amount of eggs placed in egg sock*
Organic Matter %: *Percentage of organic matter contained within the fine sediment (<2mm)*

4.4. Dissolved Oxygen Levels in 10 cm Depth of Substrate and 20 cm Depth of Substrate

River Langvad

Figure 3 presents the average oxygen levels in the 10 cm and 20 cm depths within the simulated redds in both rivers. In figure 3, for the first 8 weeks of the study, the oxygen levels remain high in both the 10 cm and 20 cm level, between 9 and 12 mg/l of dissolved oxygen which is above the critical limit for brown trout eggs at that development stage. Around the 8th (05/03/03) week both the 10 cm and 20 cm levels decrease to potentially lethal levels for the eggs present at that stage. This could have been the reason why no survival was recorded in any of the levels in River Langvad.

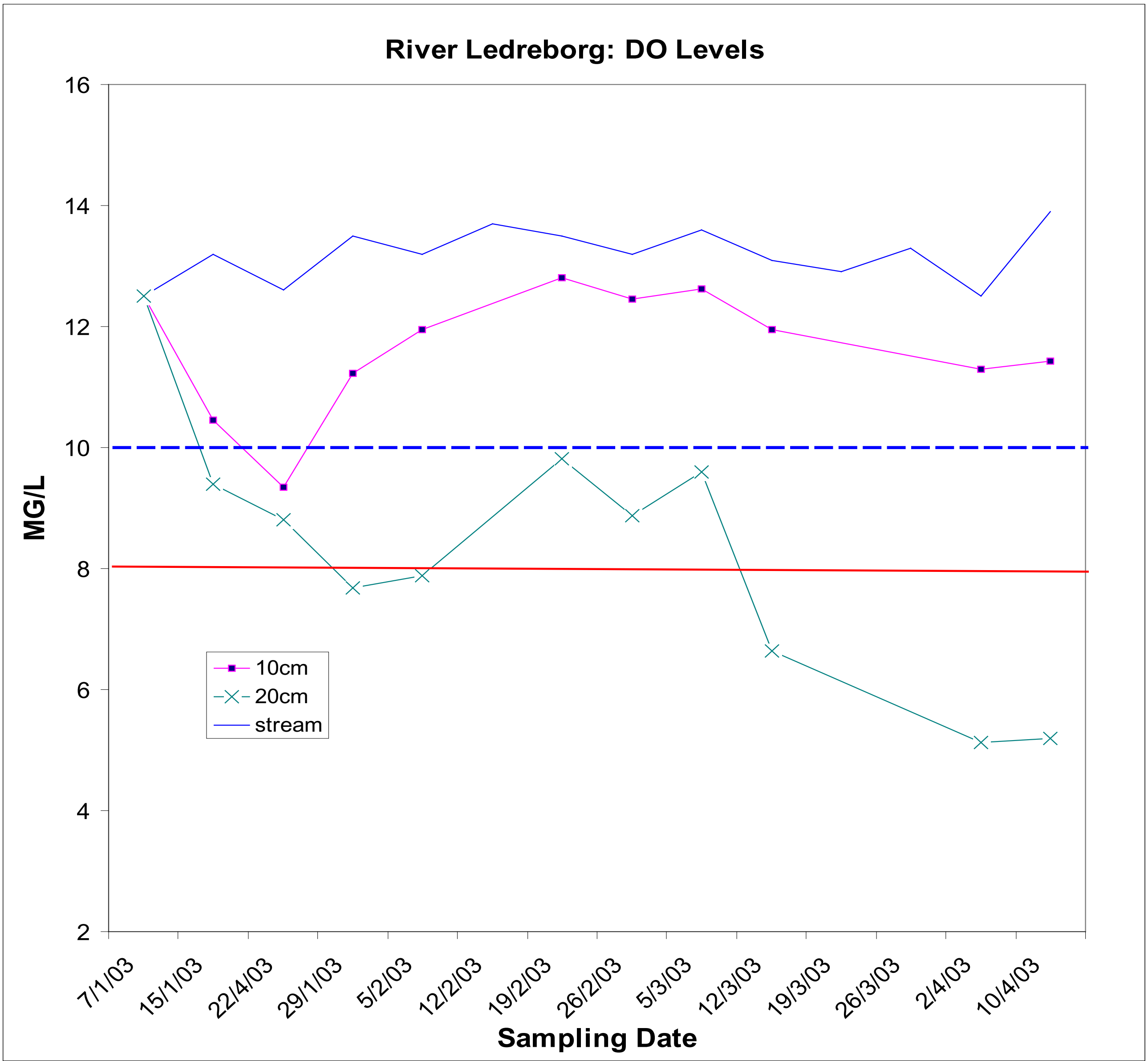

Figure 3. *The levels of dissolved oxygen in River Langvad. The unbroken line indicates the critical limit of 8mg/l of DO needed for hatching to emerging to be successful in brown trout alevins. This critical limit is used by many authors (Davis 1975). The broken line is a critical limit proposed by Swedish authors (Rubin and Glimaaster 1996)*

River Ledreborg
Figure 4 shows that for the 10 cm level the oxygen levels for the entirety of the study never dropped below the 8mg/l critical limit. However, in the 20 cm level it dropped (as in River Langvad) after week 9 and remained below the critical limit for the remainder of the study.

The high levels of dissolved oxygen experienced in the top 10 cm of River Ledreborg could explain why some alevins survived despite high concentrations of sediment in all replicates.

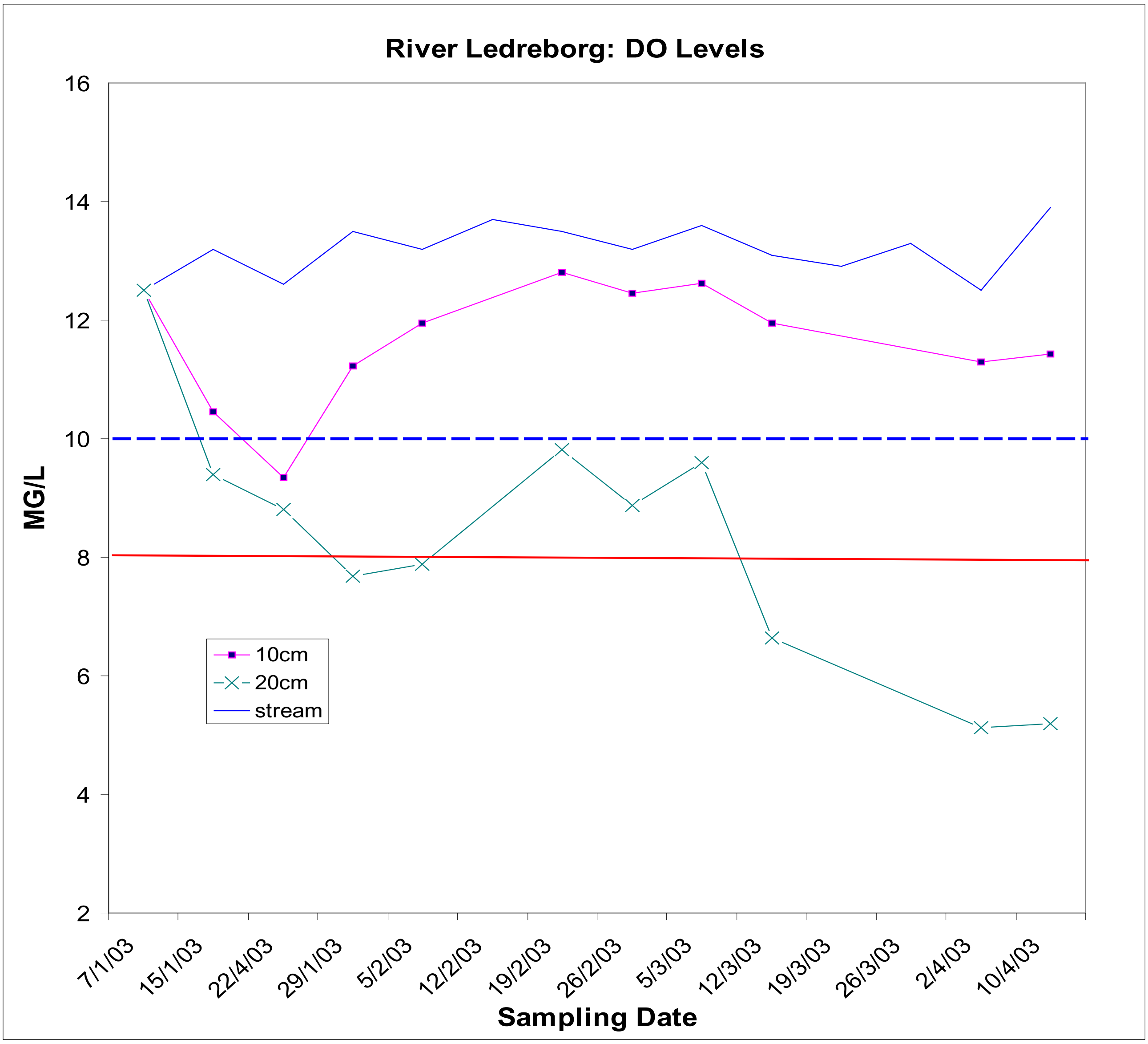

Figure 4. *The levels of dissolved oxygen in River Ledreborg*

5. Discussion

5.1. Sedimentation and Surviving Alevins

The effects of sediment deposition within salmonid spawning grounds have been extensively studied in many areas of the world, especially in the USA where many of the salmonid spawning grounds are of great commercial importance (Elliot 1994). Europe has also extensively studied the relationship between sediment and spawning grounds (Rubin and Glimaaster 1996, Laine *et al.* 2001). An inverse relationship between quantity of fine sediment, egg survival and fry emergence has been demonstrated on all continents containing brown trout.

On average the sediment levels in both River Langvad (12.7%) and River Ledreborg (24%) were well above the hatching – emergence critical limit, so minimal survival would have been expected in both streams. However, if sedimentation was to be the sole factor explaining why brown trout are not naturally recruiting in River Langvad, then it is not clear why there was still some survival at even higher levels of sedimentation in River Ledreborg.

Other factors such as organic matter or other pollution that affects dissolved oxygen levels may be contributing to preventing recruitment in the River Langvad. These factors will be explained in the following sections.

5.2. Dissolved Oxygen Levels in Both of the Rivers

Sedimentation would have been the major factor in why the DO levels dropped however, the compilation of fine sediment entering the nests and the time of the year may have played a bigger role than just fine sediment alone in determining why the DO levels suddenly dropped after nine weeks of incubation. If a storm event had occurred and a large amount of sediment had entered the stream then a steep decline in DO levels could be expected as the fine sediment transported into the stream infiltrated into the spawning gravel. However, no storm events occurred at this time or at any time in the study. It would have been expected that DO oxygen levels would decrease gradually over time, as more sediment infiltrated the gravel, and not start a rapid decline at a certain stage (Sear 1993). No other anthropogenic events (e.g. treatment plant overflow) were observed during this period so it is not expected that they would be responsible for this decline in DO levels (Henriksen 2003 – pers comm).

5.3. Percentage of Organic Matter (OM)

As temperature increases, so does the breakdown of OM and therefore the use of DO. If the OM is made up from easily broken down material such as organic material from wastewater treatment plants, then DO levels can rapidly decrease as organisms breaking down the OM utilise the surrounding DO, especially as temperatures in the stream increase e.g. as spring approaches. For this process to occur, River Langvad must have contained easily broken down OM. This source of OM is usually derived from the incomplete removal from wastewater treatment plants and River Langvad has at least five rather small treatment plants situated upstream from the site. A much larger one that has tertiary treatment is situated at least eight kilometres upstream. The effluent that is released into the stream is biologically treated from four of the five small treatment plants upstream from the site and mechanically treated in one. Biological treatment during the cold winter months is very inefficient at removing OM (i.e. the process is temperature dependant). If wastewater is allowed to enter the stream in winter months, sufficient amounts of OM can be transported into the spawning redds, and as stream temperatures begin to rise breakdown of the OM begins and DO levels will decrease (Helmgaard and Rasmussen 1995, Rubin and Glimaaster 1996).

Another source of easily broken down OM could be coming from rural dwellings that are not connected to the main wastewater treatment plants and rely on septic tanks to facilitate their wastewater. If wastewater is to escape from these septic tanks and enter the stream, it can add huge amounts of OM, as it is completely untreated. The wastewater from a few houses can impact a small stream just as much as the treated wastewater from a whole city impacts a major river (Bach *et al.* 2001). River Langvad has many of these dwellings situated along it, and they could easily be a source of such OM. Managing authorities have recorded BOD levels as being the highest in the River Langvad at the same time DO levels decrease and River Langvad also has a macro-invertebrate fauna class (Danish ecological quality test) that indicates the stream is being moderately affected from organic pollution sources such as easily broken down OM.

5.4. Combination of Factors

It is more than probable that the interaction of several factors may have been responsible for the death of all developing brown trout within River Langvad. Relatively high percentage fines would have prevented adequate intragravel flow of water and, therefore, reduced the amount of dissolved oxygen available to the developing brown trout. The fine sediment could have carried with it easily biodegradable organic matter that degraded as the stream temperatures increased. This OM breakdown, as well as the level of sedimentation, could have easily contributed to the low levels of DO recorded at such a critical stage in the developing brown trout's lifecycle (hatching to emergence). Temperature could also have influenced survival. If the development had been delayed by low temperatures or the embryos weakened by such low temperatures recorded in the stream, the developing brown trout would have been less able to combat the effects of other detrimental factors such as increasing sediment (Laine *et al.* 2001).

Overall, my findings would support the work of previous authors suggesting that sedimentation is a problem that limits the natural recruitment of brown trout. My findings also suggest that sedimentation is a problem in River Langvad and is having a direct effect on the developing brown trout either by lowering DO levels physically by reducing the intragravel flow and therefore the amount of DO flowing to the developing brown trout; or through the breakdown of OM contained within the fine sediment. More surprising is the finding of such high sedimentation in the 'pristine area' of River Ledreborg.

Table 2 ranks the different factors affecting the streams that were tested during the study. The table shows how it is important to look at different affecting factors cumulatively rather than singularly as many factors may be negligible in their effects singularly but when combined with other effects can prove lethal.

Table 2. Ranking of possible causes for low natural recruitment levels in both streams

Probabilities of Impact on Survival Percentage

	River Ledreborg	River Langvad
Sedimentation	+++	+++
Dissolved Oxygen	++	+++
Temperature	-	+
Organic Matter	+	+++*
Water Quality	-	+

*Has not been proven

+++: *Severe effect on survival percentages of Brown trout*
++: *Significant effect on survival percentages of Brown trout*
+: *Possible effect on survival percentages of Brown trout*
–: *Negligible effect on survival percentages of Brown trout*

6. Recommendations

For natural recruitment levels of brown trout to improve in the two streams both short-term and long-term strategies will have to be implemented. Some short-term strategies will become ineffective and remain costly if the long-term strategies are not implemented fully and adhered to by all involved parties. The recommendations given in this report are both achievable and are already implemented in other areas of Denmark with similar problems. They are also in line with the current view or philosophy on managing streams i.e. working with the stream and not against it to meet management needs.

River Langvad

There are currently no new ventures about to commence to improve natural recruitment levels of brown trout in River Langvad. Below are some recommendations of strategies that could be implemented to increase the natural recruitment levels. They are specifically directed at sediment control.

Recommendations for Short-term Management Strategies

- A sediment trap should be placed directly above the area of spawning gravel at the study site. Another study on the island of Funen (Nielsen 2003) showed that sediment traps can become ineffective at enhancing survival rates of brown trout as little as 200m downstream of the trap. Although sediment traps are relatively high maintenance, especially when there are high amounts of sediment in the stream, it would be feasible as a large amount of time, money, and effort went into placing spawning gravel in this section.

- Fine sediment sizing needs to be done to establish the size ratio of the fine sediment and then this knowledge needs to be applied to establishing the length of the sediment trap. The smaller the particles, the longer the trap to allow settling.

- Sediment sourcing experiments should be conducted to find the biggest contributors of sediment to the stream and when defined appropriate measures taken to reduce the sediment from entering the streams.

- The organic matter components of the sediment load in the stream need to be further investigated to determine the constituents of the organic matter. If it is found to be easily broken down organic matter, then its sources must be identified and the problem rectified.

Recommendations for Long-term Management Strategies

- The promotion of riparian zones and the encouragement of the 2 – 10m wide buffer zones must be implemented. As well as preventing sediment from entering the stream it can provide many other benefits. High runoff areas from fields must have even wider and more heavily vegetated buffer zones to prevent sediment entering the stream.

- Environmentally Sound Maintenance (ESM) should be continued in the stream. Methods such as cutting aquatic plants to form a sinuous channel, cutting manually and only when necessary, and weed cutting with minimum sediment disturbance should be strictly adhered to. Unfortunately this long-term strategy can become ineffective if sediment load continues to be high, so the prevention of sediment entering the stream should be the highest priority. ESM would also reduce instream erosion and enhance the distance in which the sediment trap was effective.

- The continual involvement and promotion to community groups e.g. the local fishing clubs and more importantly the local landholders about stream issues such as sedimentation. Local landholders must be made aware of what impacts they could be having on the stream that runs through their property.

River Ledreborg

As in River Langvad, there are currently no new ventures about to commence to improve natural recruitment levels of brown trout. River Ledreborg would benefit from implementing the short-term strategies described for River Langvad. The long-term recommendations are strategies targeted specifically for River Ledreborg to increase the natural recruitment levels. If implemented these strategies would be very effective at controlling sediment and increasing natural recruitment levels in the stream.

Recommendations for Long-term Management Strategies

- Stretches of stream where forest does not cover the banks must have riparian zones established and the 2m buffer zones enforced. A substantial amount of the stream has already been fenced off to stock and all remaining areas must also have the access of stock prevented.

- Barriers should be removed or altered as encouraged by Roskilde County. Sediment becomes a bigger problem the further you go downstream and due to fish barriers, anadromous brown trout are prevented from entering less sediment affected spawning grounds further upstream.

- Forest roads are probably a major contributor of fine sediment directly to the stream, especially the spawning ground where the study site was situated. All runoff from these roads must be directed onto the forest floor so the road runoff is devoid of sediment when it reaches the stream.

7. Conclusion

Sedimentation is a major factor limiting natural recruitment of brown trout in both streams within the Kornerup catchment. Although knowledge of sediment-salmonid interactions is incomplete, some principles for sediment management are apparent. Brown trout are well adapted to Danish streams. Brown trout are able to cope with the natural spatial and temporal variability in fine sediments in these stream systems, but populations can become stressed or reduced by sedimentation that persistently exceeds natural levels under which the stock evolved. Sediment control must be viewed on a more holistic scale. Although anthropogenic fine sediment is an important pollution component of stream environments, its control and effects must be considered within the context of stream ecosystems. Stream managers should aim to maintain the overall integrity of streams and streamside zones rather then concentrate on one variable such as sediment. However, short-term sediment reducing strategies will aid in increasing the natural recruitment of brown trout in Danish streams.

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