Ecosystem response to dam removal

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Cover: Remains of the Unnefors and Kuba dams. Photograph by Anna Lejon
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To Tilda & Elsa

List of papers

This thesis is a summary of the following papers, referred to in the text by their Roman numerals:

I	Lejon, A.G.C, Renöfält, B.M. and Nilsson, C. (2009) Conflicts associated with dam removal in Sweden. *Ecology and Society*, 14: 4
II	Lejon, A.G.C, Renöfält, B.M. and Nilsson, C. Dam removal effects on riparian vegetation. *Manuscript*
III	Lejon, A.G.C, Renöfält, B.M. and Nilsson, C. Succession of riparian plants following dam removal in a boreal stream in central Sweden. *Submitted manuscript*
IV	Malm-Renöfält, B., Lejon, A.G.C., Jonsson, M. and Nilsson, C. Long-term taxon-specific responses of macroinvertebrates to dam removal in a mid-sized Swedish stream. *Submitted manuscript*

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ABSTRACT

This thesis aims to improve our understanding of how riverine ecosystems respond to dam removal. Riverine and particularly riparian ecosystems are among the most variable and important features of all landscapes. They connect landscape elements both longitudinally and laterally, and are governed by processes such as flooding, erosion and deposition that create dynamic, diverse and heterogeneous habitats. In fact, riparian zones are among the world's most species-rich habitats. Worldwide there are millions of dams that fragment stream and river systems, regulate flows and degrade ecosystems. Dams impact freshwater, marine and terrestrial ecosystems and threaten biodiversity by disrupting organism movements and energy flows in the landscape. An important upstream effect of dams is inundation of habitats and development of new shorelines around impounded areas. Effects downstream of dams are mainly caused by changed hydrological regimes and retention of organic and inorganic materials in reservoirs, leading to reduced transport and dispersal of for example seeds to reaches downstream. The removal of dams create expectations that biota will eventually recover. We have studied a number of dam removal projects in Sweden. Our experimental results showed that following dam removal, newly exposed soils in former impoundments were rapidly colonized by pre-removal species. Their species richness increased slightly with time and their species composition indicated a slow change towards that in the reference site. In addition, the vegetation in formerly impounded areas showed a direction of change from lentic riparian plants (high proportion of aquatics) towards lotic ones, consisting of native perennials typical of free-flowing streams. We also found that the apprehensions that former impoundments would turn into pools of mud did not come true; in fact, a process towards more pristine channel morphology was observed. After removal there was erosion and downstream transport of sediment. We found only minor effects on macroinvertebrate communities. For example, a few species decreased over the years, suggesting that dam removal in itself might cause a temporary disturbance. This highlights the importance of long-term studies after dam removal, and also the importance of comparisons with pre-removal conditions and stretches unaffected by dams. Thorough documentation of executed dam removal projects and distribution of the results and experiences are tremendously important in the planning process of future decommissioning projects. Also, our experiences have taught us that in order to attain a successful dam removal it is important to involve stakeholders such as non-governmental organizations and local inhabitants in the process.

Keywords: dam removal, macroinvertebrates, plant species, plant succession, restoration, riparian zone, sediment deposition, species richness, Sweden.

INTRODUCTION

Dams and reservoirs have been built for centuries to meet flood control, irrigation, energy, transportation, and consumption needs (WCD 2000; Nilsson et al. 2005). Human control over freshwater flow has increased the prosperity for many people but it has also led to disquieting effects on local human societies and the ecosystem (Nilsson and Berggren 2000; Scudder 2005). Benefits gained from dam construction are often intertwined with positive correlations between the dam and economic growth. This is a distorted image because the number of people that benefit from dams is usually exceeded by the number of people who suffer adversely (WCD 2000). There are globally about 50 000 large dams above 15 m height (WCD 2000; Scudder 2005) and more are planned or under construction (WWF 2004). There is no current record on the global number of small dams (i.e. < 15 m high) but a reported count of more than 2 million such dams in North America alone (Shuman 1995; Graf 1999) gives an idea of the current widespread distribution of both large and small dams. Among Sweden's more than 5300 dams, approximately 5100 (96%) are small (SMHI 1994, 1995). Globally there are 16.7 million reservoirs larger than 0.01 ha, and 7.6% of the world's rivers with average flows above 1 $m^3 s^{-1}$ are affected by an upstream reservoir capacity that exceeds 2% of their annual flow (Lehner et al. 2011). Rivers and streams flow through many geographical regions and are therefore rarely confined to only one political or jurisdictional area. Since many regulated rivers have storage reservoirs in headwater regions, the flow in the entire river is ineluctably affected (Nilsson and Berggren 2000).

Riparian ecosystems

Riparian ecosystems are among the ecologically most important features of landscapes and fluvial processes such as flooding and sediment erosion and deposition are tremendously important when structuring riparian plant communities (Nilsson and Jansson 1995; Nilsson et al. 1999; Helfield et al. 2007). Riparian zones are characterised by high species richness which is governed by the hydrological regime, i.e. timing, duration, magnitude and rate of change in flow. These variables are involved in creating habitats with high heterogeneity (Naiman et al. 1993; Poff et al. 1997; Ward et al. 1999; Arthington et al. 2006), favourable to most riparian plant species which depend on or withstand recurrent floods. Diaspores can spread long distances in rivers and streams which makes the riparian zone an effective pathway for plant dispersal (Nilsson et al. 1991; Johansson and Nilsson 1993; Jansson et al. 2000). Fragmented rivers and streams are less species rich, and the cover of riparian plants is in general lower than in free-flowing ones because of the barriers dams constitute (Jansson et al. 2000).

Ecological effects of dams

Most dams are built to ensure less variability in flows downstream, which is attained by irregular and increasingly fluctuating water levels in the impounded area behind the dam. Other dams are built to facilitate diversion of water, which strongly reduces water flow downstream and in many cases leaves the channels permanently or intermittently dry. Consequently, many rivers and streams lose their rapids (Nilsson and Berggren 2000). Freshwater systems are vulnerable to biodiversity decline, and streams and rivers are both receivers and distributors of stressors from the catchment. Because dams alter stream flow and sediment transport regimes, riparian and upland ecosystems, as well as estuarine and marine communities, are impacted both physically and ecologically (Pringle et al. 2000; Syvitsky et al. 2005; Freeman and Marcinek 2006). Except for destroying riverine structures and processes, reservoir inundation also impedes dispersal and migration of riparian and aquatic organisms (Ward and Stanford, 1995; Jansson et al., 2000; Kingsford, 2000; Hart and Poff 2002; WWF 2004; Syvitski et al., 2005; Renöfält et al. 2010). Inevitably, these impacts damage ecological communities and erode the soil of inundated land (Dudgeon 1995; Nilsson et al. 1997).

Dam removal

Today, many dams are non-functional except for being barriers and during the last decades many such dams have been removed (Hart and Poff, 2002; Lejon et al. 2009). Dam removal is motivated by safety, economy, loss of capacity and out-dated technology (David and Baish 2002; Palmer et al. 2004; Bernhardt et al. 2005). An increasingly common cause for dam removal is ecological restoration of streams and rivers (Bednarek 2001), yet despite potential benefits, local stakeholders often oppose removal. One fear is that exposed sediments in former impoundments will remain barren, thus reducing aesthetic values (Lejon et al. 2009). Removal of entire impoundments, dams and hydropower plants in order to restore riverine habitats is a new practice in Sweden, but many small dams – especially those built to serve timber floating – have been removed over the years (Christer Nilsson, *personal communication*). Dam removal is becoming a more frequently used management option, especially for old dams in need of renovation, constituting a safety hazard, and small dams that are no longer used or have lost most of their reservoir capacity. For the dam owner, removal can be economically preferable to renovation, whereas environmental benefits gained from restoration of turbulent stream reaches and fish migration routes can be important (Stanley and Doyle 2003). Dam removal promotes a more heterogeneous environment for aquatic invertebrates (Vinson and Hawkins 1998; Kibler et al. 2011) when factors such as channel bed morphology, temperature, water quality etc. are allowed to recover (Ward 1995; Renöfält et al. 2010). In contrast, dam removal may also act as a moderate disturbance and initially reduce density and taxonomic richness, while invertebrate community composition remains largely unchanged (Doyle et al. 2003; Thomson et al. 2005; Orr et al. 2008).

MAIN OBJECTIVES

The aim of this thesis is to improve our understanding of the ecological effects of dam removal on local plant and macroinvertebrate communities. The main objectives can be summarized by the following questions:

- What are the main incitements and obstructions to removing a dam? Also, what conflicts do stakeholders and restorationists face when planning and executing a dam removal? (**I**)

- How do dam removal and restoration affect hydrological variables such as water velocity and flooding, and how do riparian plant communities respond? (**II**, **III**)

- What short- and long-term effects does dam removal have on macroinvertebrate communities? (**IV**)

STUDY AREA

Two study sites situated in rural areas were used. The first study site was located in a medium-sized stream in the southern temperate region of Sweden. The second study site was situated in a large stream in the central boreal region of Sweden. The streams are characterized by tranquil reaches intersected by rapids. In the central boreal region, water levels are highest during spring flood in May–June and lowest during winter. In the southern temperate region, water levels are highest in March–April. Spring floods tend to come earlier for each year in southern Sweden due to milder winters and precipitation coming as rain instead of snow (SMHI 2009). Sand and gravel are the dominant substrates in the central Swedish study site, and till in the southern site (Fredén 1994). The vegetation in the southern area is dominated by mixed coniferous forest. In the central Swedish study site the vegetation is dominated by grey alder *Alnus incana* (L.) and Norway spruce *Picea abies* (L.) H. Karst. Vegetation was nonexistent in the new riparian zones along the former reservoirs immediately after dam removal but within months graminoids and tall herbs (mostly *Carex*) invaded the bare sediment banks.

METHODS

For paper **I** we sent out questionnaires to all the municipalities and county administration boards in Sweden where we called for information regarding known dams and dam removals (performed or halted), conflicts and issues involved in the process along with the main reason for removal. We also asked for the end-result and their conclusions about the work and process. Answers were collected by mail and e-mail. For papers **II** and **III** we recorded presence of all species (except bryophytes) rooted within 50×200 cm large plots along with the percentage cover of vegetation (vertical projection going from 0 to 100%) up to 0.5 m above ground. We also quantified environmental factors such as shading from overstorey cover, and proportions of substrate size classes were measured and divided by Wentworth grain sizes supplemented by peat and bedrock (Chorley et al. 1984). Soil moisture was measured using a soil moisture meter (Theta Probe ML2x, Delta-T Devices, UK). Biomass productivity was measured by cutting all aboveground vegetation within an area of 20×20 cm just outside the sample site's upper right corner facing upstream. After harvest, biomass was dried at 60°C for 72 hours in a Memmert oven and then weighed. Sediment deposition was measured by placing 15×15 cm polyethylene Finnturf® mats outside the lower left corner of the sample site facing downstream. The mats were collected after 12 months and then dried to constant weight in room temperature. For paper **III** the elevation of the plots and topography of the sites were measured with a total station (an integrated electronic theodolite and distance meter; Geodolite 506, Trimble, Sweden). We also measured local water levels using pressure transducer data loggers (Diver®, van Essen Instruments Limited, the Netherlands) that recorded the depth of the water column on top of the logger, hanging in a well placed in the stream. Another logger measured air pressure, and the differences between air and water loggers provided the water level at a specific period of time. In paper **IV** we collected benthic invertebrates. Each sample, evenly distributed over each reach, was obtained by kicking a sample location (35×100 cm) for 60 seconds. The collected invertebrates were identified to lowest possible taxonomic level. Also, sediment deposition was measured using the procedure described above.

SUMMARY OF PAPERS

(I) Conflicts associated with dam removal in Sweden

This paper stems from our own experiences with completed, delayed and disrupted dam removal projects in Sweden. We wanted to shed some light upon the bumpy road that lies ahead of everyone in the starting blocks of monitoring the effects of a dam removal. We mapped four incentives for and three obstructions against dam removal. For several reasons dam removal is nowadays becoming a viable option when working with stream and river restoration. Removal of a dam can in most cases be much cheaper for the dam owner than renovation (Stanley and Doyle 2003). Despite all the benefits, however, dam removal often gives rise to conflicts which result in long processing times and/or cancelled removals. We presented safety, law and policies, economic and ecological reasons as strong incentives for dam removal. The major obstacles are financing, cultural-historical values and threatened species.

Dams and reservoirs are not designed for discharge outside their range of variability, so increased discharge due to climate change (Palmer et al. 2008) and high sedimentation rates in the reservoir (Evan et al. 2000) are two major stressors on a dam. Since dams have limited life spans they need to be maintained properly or they will eventually break (David and Baish 2002; Palmer et al. 2008). Dams at risk of failure cause serious threats to humans and infrastructure. The Swedish Environmental Objectives state 16 ecosystem goals and the objective most relevant for freshwater ecosystems concerns the responsibility of maintaining flourishing lakes and streams, and a rich diversity of animal and plant life (Swedish Government 2011). Also, strong national law and policy instruments may be imperatives for dam removal. By signing the European Water Framework Directive, member states have agreed to manage all waters in an ecologically sustainable way and to maintain their ecological status (European Commission 2000). Furthermore, the European Union Natura 2000 network and the Habitat Directive oblige the member states to ensure restoration or maintenance of natural habitat (European Commission 1992). Within these directives lie both the opportunity and the obligation to restore degraded waters that for example have been dammed. In many cases it may be economically beneficial to remove than to keep a dam, mostly because of maintenance and renovation costs. The cost to repair a dam can be as much as three times higher than to remove it (Born et al. 1998). A common consequence of damming rivers is an impoverished fish fauna. Fish production is often an important source of income for local inhabitants, both directly as fish harvest and indirectly as a resource base for tourism and recreational fishing. The loss of income caused by the loss of fishing can be greater than the value of the power produced (Kruse and Scholz 2006). The restoration of fishing can therefore be a strong incentive for removing dams. The reindeer herding Sami people have been profoundly affected by dams and reservoirs because of the inundation of river valleys. Also, the passage of rivers during migration periods has become difficult because of modified flow and ice conditions (Morin 2006).

Dams alter many natural characteristics of and processes in rivers such as sediment dynamics, productivity, modification of temperature regimes of downstream reaches and shifts in biota (Gregory et al. 2002; Hart and Poff 2002). Climate change may be an important reason for dam removal. Globally, some rivers may face increased discharge whereas others may experience a considerable flow reduction. With increasing temperatures, reservoirs in warm and dry areas will lose even more water than they already do through evaporation. Also, the large amount of sediments trapped in reservoirs reduces the nutrient supply to the sea and causes deltas to shrink (Ericsson et al. 2006; Palmer et al. 2008). Dam removal is a feasible method for restoring habitats, flow patterns, and migration paths. It is possible to restore these three riverine components separately or in various combinations depending on the results required.

Funding for dam removal must come from several different sources since expenses usually are too high to be covered by a single financer (Babbitt 2002). To be able to argue for a removal and allocate funding it is crucial to have good knowledge about the economic consequences involved. There is no guarantee that the allocated funds will cover all the costs because there are many stakeholders in the process to account for. Cultural-historical values are important to consider but they are a snag no matter how negative effect the dam may have on the ecosystem. Since many of these structures are old and historically important in many communities it is difficult to balance the importance of functioning ecosystems and cultural-historical values. Therefore, the Swedish EPA and several of the county administrative boards cooperate with the National Heritage Board to ensure good decision making.

Dams are barriers for migrating and dispersive species, native as well as invasive. Removing a dam exposes a large area of sediment which is highly conducive to plant colonisation. Aggressive plant colonists may prevail for years if native species fail to survive due to competition from these invasives (D'Antonio and Meyerson 2002; Shafroth et al. 2002; Orr and Stanley 2006). Dams prevent aquatic organisms in their seasonal migration, and the diversity and productivity of aquatic habitats are reduced because of lost connectivity in the aquatic ecosystems. There is always a risk that when a dam is removed and the river restored, non-native species may spread and homogenize the aquatic biotas. However, when former impoundments are restored to free-flowing waters, fish composition will shift from lentic to lotic, thus allowing native species to return and consequently increasing biotic diversity (Rahel 2007). This is a process that takes time; riverine organisms are always more or less affected by a dam removal before the state in the channel has stabilized. Some faunal changes may occur rapidly, whereas other long-term changes occur as species adjust to the changes (Hart et al. 2002).

We also looked at 17 Swedish dams and rivers subjected to or considered for restoration. We presented the reasons for removal or compromise and the issues involved in the process. The main reason for removal was to ensure fish passage while increased biodiversity came second. During the compilation process it became clear to us that practically every case comprised unwillingness to collaborate, misconceptions and strong wills in general. It is a common apprehension that when a dam is removed there will be nothing left than a pool of mud (Sarakinos and Jonson 2003). Public perceptions of a dam removal and its consequences may intercept removal projects. Change is a word humans tend to shun and therefore it is crucial to educate and carefully explain benefits and effects of a removal to the public, and also to keep them, as well as the stakeholders, informed during the process.

(II) Dam removal effects on riparian vegetation

In this paper we present a study of the vegetation in riparian reaches upstream and downstream of a dam construction in the Nissan stream in southern Sweden before and after its removal, using a Before-After-Control-Impact (BACI) design (sensu Green 1979). The strength with the BACI study design lies in the fact that differentiation between changes related to dam removal and changes caused by other factors is allowed (Kibler et al. 2011). The Unnefors dam constituted one of the last impediments for fish to migrate freely in the uppermost parts of Nissan main channel. We monitored the vegetation and different environmental variables at three different water levels (summer low, middle and spring high) in the impoundment, downstream of the dam, and in an unimpacted reach located within the same river system upstream of the area affected by the dam. Orr and Stanley (2006) and Lejon et al. (*unpublished data)* documented fast colonisation in the former impoundment already after the first growing season after dam removal and that was also noted in Nissan stream; plant colonization was fast on newly exposed soils in the former impoundment and species richness increased slightly without major changes of the dominant species. However, although the colonizing vegetation was similar to that of the former impoundment it showed a tendency to have changed from lentic to lotic characteristics (cf. Auble et al. 2007). The reach downstream of the dam exhibited minor changes after dam removal, comparable to those in the reference reach. The fact that the post-removal vegetation in the impoundment area was most similar to that of the previous impoundment suggests low seed rain and local recruitment (cf. Michel et al. 2011). Dam removal should initiate ecological recovery but often there is a shortage of measurable criteria for ecological improvement that makes it difficult to judge whether it has reached the desired goals (Palmer et al. 2005; Bernhardt and Palmer 2011; Violin et al. 2011). Several studies show that recovery after a dam removal takes time (Orr and Stanley 2006; McBride et al. 2010) and to expect vegetation in a former impoundment to show pre-impoundment plant composition at an early stage might be presumptuous.

In conclusion, we saw that local plant communities responded quickly to dam removal when the former impoundment was drained and emptied, and fine-grade sediments were exposed. The major vegetation response in the former impoundment was an invasion of pre-removal, riparian species, reflecting conditions in the reach.

(III) Succession of riparian plants following dam removal in a boreal stream in central Sweden

For this paper we studied the succession of plant communities in riparian sites upstream and downstream of a recently removed dam in central Sweden. The study was conducted over 3 years and we compared vegetation development with a reference site in an unimpacted reach within the same catchment. When the impounded area was drained, a stretch of rapids was exposed in its uppermost reach. Previous studies in former reservoirs have shown that the amount of bare ground decreases and vegetation establishment is fast already after the first growing season (Orr and Stanley 2006) so that was expected here as well. Also, Helfield et al. (2007) found that restoration of streams used for log floating favoured riparian vegetation diversity, and Jähnig *et al.* (2009) showed that channel reconstruction in Central European rivers increased plant species richness on floodplains. We recorded water level fluctuations, and 2 years after removal we observed significant relationships between species richness and flood duration (cf. Jansson et al. 2000; Kozlowski 2002). Plots located in the former reservoir were most affected by dam removal. Plant colonization was fast in the new riparian zone in these plots, and over the study period species composition became more and more similar to that of the reference reach. The sites in the former reservoir were rich in fine sediments and showed significant changes in the proportions of species groups between years. There was a large spring flood in 2008 and floods are known to favour plant production by depositing nutrient-rich sediments (Robertson et al. 1999). Biomass production was highest in the former reservoir, and this coincides with favourable environmental conditions such as light availability. The riparian vegetation in the downstream reach was relatively stable in species composition after dam removal, implying that community composition was little affected by dam removal.

The dam removal was reasonably successful in restoring species composition in the former reservoir, indicating that an appropriate species pool has been available and conditions for natural regeneration of riparian vegetation are sufficient. However, there was a significant decline in species richness in the downstream reach which may imply that the upstream and downstream effects of the removal may differ and the removal itself may have acted as a disturbance on the downstream system (cf. Thomson et al. 2005; Orr et al. 2008; Renöfält et al., *unpublished data*). The stretch of new rapids is still affected by former timber floating structures and may need further physical restoration to enhance ecological values. Also, there are still four hydroelectric dams upstream of the restored stretch which may constrain a more complete vegetation recovery.

(IV) Long-term taxon specific responses of macroinvertebrates to dam removal in a mid-sized Swedish stream

In this study we investigated both short- and long-term dam removal effects on downstream macroinvertebrate communities. Thus far, there have been few studies of the effects of dam removal on stream macroinvertebrates, and the results obtained have been equivocal. Benthic communities are structured by factors such as hydraulic conditions, variation in discharge, water quality, temperature, and channel bed morphology (Townsend *et al.*, 1983; Townsend, 1989; Death and Winterbourn, 1995). Dams alter several of these factors (Ward, 1985; Renöfält *et al.*, 2010) with potential consequences for downstream benthic communities. Dam removal can be expected to make a reach more natural in a long-term perspective, but it can also be expected to initiate changes in the system that may act as a disturbance on downstream communities, for example by mobilizing sediments accumulated in the reservoir. Doyle et al. (2003) found that major changes in sediment structure followed within 5 years of removal and was similar to that of extreme natural flooding. We performed a before-and-after study of the removal of a dam located in a south Swedish stream. Benthic sampling took place 6 months prior to dam removal, 6 months after removal, and to evaluate long term effects, 3.5 years after the dam was removed. We compared species composition, taxonomic richness, total densities, and densities of macroinvertebrate groups before and after removal and between downstream and reference sites. We found negative effects of dam removal on some macroinvertebrate taxa, but no effect on community composition. While this is in line with results from previous short-term studies, we also found a negative effect on taxonomic richness and that some dam removal effects persisted or even increased over time. The most likely explanation for negative effects of dam removal is an increased sediment transport from the former reservoir, and subsequent loss of preferred substrates. The continuous decrease in macroinvertebrate taxonomic richness emphasises the need to also investigate how rates of ecosystem processes are influenced by dam removal. Our results indicate that adverse dam removal effects may be longer-lasting, but taxon specific, and therefore there is a need for long-term studies on a variety of organisms to better understand how dam removal may influence downstream macroinvertebrate communities.

CONCLUDING REMARKS

We tend to use nature as our sandbox in which we dig, build and tear down our constructions as we please. Inevitably this leads to ecosystem effects that are difficult, if not impossible, to repair when mistakes and miscalculations are revealed. Even though only a small fraction of all ecosystems can be restored or rehabilitated it is crucial that restoration practices are appropriately and effectively performed in order to enhance ecosystem functioning. This often means that ecosystems are given opportunities to recover by themselves and not that restoration is taking them to a final, completed stage. As a matter of fact, ecological restoration is usually defined as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 2004). Dam removal is becoming an increasingly common and accepted tool in the attempts to restore degraded and fragmented streams and rivers. For various reasons, several dam removal projects in Sweden have never come to an end due to for example poor planning, misjudgement and opposition. Unfortunately, documentation of performed and/or halted removals leaves more to be desired. In order to learn from previous decommissioning projects it is vital to evaluate their development and draw conclusions from their results. As a consequence, solid documentation would facilitate thorough decisions regarding future dam removals, and also enhance their planning and execution.

Previous studies have shown that water-level regulation of streams and rivers is followed by a decrease in plant production and species richness in the riparian zone (Jansson et al. 2000; Kozlowski 2002). Restoration of water-levels should thus provide an opportunity for vegetation recovery and this was observed in our studies, although it happened at a slow pace. In general, species richness did not change significantly after dam removal in the former impoundment, but to judge from indications in our studies, with time species composition is expected to become increasingly similar to the one in reference sites. Also, we noted that the successional trajectory of vegetation in newly exposed riparian areas was directed from lentic (high proportion of aquatics) towards lotic riparian vegetation of native perennials typical of free-flowing streams. Similar rapid changes in plant species composition were also found by Auble et al. (2007) on old impoundment bottoms after a 4-year drawdown of the water-level in a reservoir in Colorado, USA. A common misunderstanding is that removal of a dam will leave exposed sediments barren and that the former impoundment will turn into a pool of mud (Lejon et al. 2009). Our results have proven this to be incorrect and they show, on the contrary, that vegetation establishment on bare and newly exposed sediment banks can be fast (cf. Doyle and Stanley 2006). After dam removal there is much accumulated sediment that is being flushed and transported away with inevitable downstream effects. We have demonstrated a small, yet temporary effect on downstream macroinvertebrate communities. There was, however, a continuous decrease in taxonomic richness and we cannot tell whether it will be reversible or not. This implies that dam removal in itself might act as a disturbance factor. Since biodiversity is tremendously important for the maintenance of ecosystem processes (Vaughn 2010) this issues the need to investigate how rates of ecosystem processes are influenced by dam removal. Given the fact that it takes time to reach dynamic equilibrium it is crucial to aim for long-term studies in order to better understand the effects and responses of dam removal. Also, it is important to consider that removal of a dam will perhaps not be the most beneficial solution in all rivers or streams. If dam removal will do more harm than good other solutions must be considered. Again, well documented results from other studies and projects will then be indispensible.

It is my hope that the results from this thesis will contribute, in practice and theory, to the development of dam removal projects both nationally and internationally.

SAMMANFATTNING (Swedish summary)

Dammar har byggts sedan århundraden tillbaka och syftet har bland annat varit allt ifrån att dämma vatten för att få energi, bevattna åkrar och bemästra översvämningar till transporter av olika slag. Dammar, och de magasin som skapas bakom dem, har många negativa effekter på ekosystemen, på oss själva och på våra samhällen. Strandzoner längs vattendrag har en viktig funktion i landskapet genom att fungera som en länk mellan terrestra och akvatiska ekosystem. Förutom att dammar och magasin förstör de strukturer och processer som finns i och längs vattendrag, så hindrar fördämningarna migration och spridning av strandlevande och akvatiska organismer mellan dessa system. Den naturliga och positiva störning som vattendraget bidrar med i form av översvämningar, erosion och deposition skapar habitat där en stor variation av arter med olika förutsättningar kan leva. De flesta strandlevande växter behöver återkommande översvämningar för att klara sig, och därför hyser fritt strömmande vattendrag stor artrikedom. En annan viktig faktor är fröspridning som underlättas väsentligt i vattendrag utan hindrande dammar.

Runt om i världen finns miljontals små dammar. De som är högre än 15 meter klassificeras som stora och är ungefär 50 000 till antalet. I dag upptäcks fler och fler trasiga dammar samt dammar som inte längre fungerar eller som utgör en säkerhetsrisk. Även om det ekonomiskt är försvarbart att riva en damm jämfört med att renovera den motsätter sig dammägaren ofta en utrivning. Närboende är också ofta negativt inställda till att riva dammen då de befarar att det enda som blir kvar är en stor lerpöl. Det är därför viktigt att både myndigheter och forskare belyser de många positiva effekterna av en utrivning. Vegetationsetableringen är nämligen relativt snabb och redan under växtsäsongen efter en rivning ses grönskande stränder även om det i sig inte betyder att den ursprungliga vegetationssammansättningen återkommit. Efter ett par år börjar vattendraget återfå en naturlig form och strandzonen förändras och anpassas därefter.

Det händer att myndigheter, vilka ofta är initiativtagare till en dammutrivning, inte kan komma överens med närboende och andra intressenter om en eventuell dammrivning. Då är kommunikation ledordet. Det är viktigt att lyssna in alla åsikter och visa att de betyder något för själva processen. I fall där en dammrivning av olika skäl inte blir av kan kompromisser vara det näst bästa alternativet. I de allra flesta fall handlar det om fiskpassager för att ge fisken möjlighet att vandra fram och tillbaka till sina lekplatser.

Huvudsyftet med min avhandling har varit att undersöka hur strandzonen, strandvegetationen samt vattenlevande makroevertebrater påverkas av utrivning av små dammar och hur de kan återhämta sig efter den störning som dammen utgjort. Under årens lopp har vi ställts inför många problem i

samband med planerade dammutrivningar och fältarbeten. I vissa fall har år av förstudier gått om intet då planerade dammrivningar stoppats och i vissa studier har fältförsöken utsatts för stöld och skadegörelse. Alla motgångar och problem inspirerade oss till att skriva en vägledande artikel till andra forskare i samma situation. Detta resulterade i min första artikel där vi förutom hinder även diskuterar incitament till dammrivningar. I den andra artikeln undersökte vi med hjälp av fältstudier, både före och efter utrivningen, hur strandvegetationen påverkats av en dammrivning. De huvudsakliga resultaten pekade på att etablering av växter i det gamla magasinet var relativt god, gick i riktning mot en mer ursprunglig vegetation men att processen var långsam. Den tredje artikeln fokuserar på efterstudier och var en ren successionsstudie där vi undersökte hur översvämningar påverkar vegetationen och hur återetableringen av växter tedde sig i det tömda magasinet. Återetableringen i det tömda magasinet var tillfredställande och redan några månader efter utrivningen var strandzonen täckt av gräs. I både artikel två och tre har vi jämfört resultaten med en referenssträcka som är helt opåverkad av dammar uppströms. I den fjärde artikeln undersökte vi hur makroevertebrater påverkas av en dammrivning. Även denna studie bygger på data från både före och efter dammrivningen och försöken utfördes i samma vattendrag som i artikel två. De resultat som stod ut var huvudsakligen att dammrivningen i sig utgjorde en störning för vissa taxonomiska grupper men inte för själva artsamhället.

Det vore orealistiskt att anta att vattendragets och strandzonens ekosystem skulle återhämta sig som genom ett trollslag efter en dammrivning. När ett system är degraderat måste det ges tid till återhämtning. Det är inte säkert att förhållandena någonsin blir likadana som de var innan dammen byggdes men förutsättningarna är åtminstone bättre än om dammen skulle lämnats intakt. Att riva en damm medför många positiva förhållanden. Naturliga fluktuerande översvämningar ger näring åt strandzonen, en mer naturlig strandvegetation kan etablera sig, restaurerade lekbottnar leder till goda habitat för vattenlevande organismer och fisk ges möjlighet att vandra obehindrat upp- och nedströms till sina lekplatser. Så även om själva utrivningen utgör en temporär störning är det sekundärt i sammanhanget. Allt tar tid.

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AUTHOR CONTRIBUTIONS

Note: Authors are referred to by their initials

Paper I: Lejon, A.G.C, Renöfält, B.M. and Nilsson, C. (2009) Conflicts associated with dam removal in Sweden. *Ecology and Society*, 14: 4.

AGCL came up with the original idea of this paper. BMR and CN worked out the explicit design during discussions with AGCL. AGCL was responsible for all contacts with authorities, the survey and its design. The results and the contents of the paper were discussed in collaboration between the authors. AGCL was responsible for the manuscript with contributions and discussions from BMR and CN.

Paper II: Lejon, A.G.C, Renöfält, B.M. and Nilsson, C. Dam removal effects on riparian vegetation. *Manuscript*

The original idea of this paper came from CN and BMR while field design was equally developed by AGCL, BMR and CN. AGCL did all the field work preparations and data handling. Field work and data analysis were equally performed by AGCL and BMR. AGCL was responsible for the manuscript, but the paper and its results were discussed and written together by AGCL, CN and BMR.

Paper III: Lejon, A.G.C, Renöfält, B.M. and Nilsson, C. Succession of riparian plants following dam removal in a boreal stream in central Sweden. *Submitted manuscript*

This paper stems from a commission from the county administration board of Västernorrland County. The idea and field design was developed by AGCL, BMR and CN. AGCL did all the field work preparations and data handling. Field work and data analysis were equally performed by AGCL and BMR. The paper and its results were discussed and written together by AGCL, BMR and CN.

Paper IV: Malm-Renöfält, B., Lejon, A. G. C, Jonsson, M. and Nilsson, C. (2011) Long-term taxon-specific responses of macroinvertebrates to dam removal in a mid-sized Swedish stream. *Submitted manuscript*

The original idea of this paper evolved from discussions between the authors. AGCL was responsible for field work preparations. AGCL, BMR and MJ performed the field work. Invertebrates were identified by a consultant. MJ and BMR were equally responsible for data analysis. BMR was responsible for the manuscript, but the paper was discussed and written together by MJ, AGCL and CN.

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