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LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following papers referred to in the text by their Roman numerals:

I. Käiro, K., Möls, T., Timm, H., Virro, T. & Järvekülg, R. 2011. The effect of damming on biological quality according to macroinvertebrates in some Estonian streams, Central – Baltic Europe: a pilot study. River Research and Applications 27: 895–907.

II. Timm, H., Käiro, K., Möls, T. & Virro, T. 2011. An index to assess hydromorphological quality of Estonian surface waters based on macroinvertebrate taxonomic composition. Limnologica 41: 398–410.

III. Käiro, K., Timm, H., Haldna, M. & Virro, T. 2012. Biological quality on the basis of macroinvertebrates in dammed habitats of some Estonian streams, Central – Baltic Europe. International Review of Hydrobiology 97: 497–508.

IV. Käiro, K., Timm, H., Haldna, M. & Virro, T. (submitted to Hydrobiologia). The effect of channelization on the biological quality of lowland streams according to macroinvertebrates.

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KK – Kairi Käiro, HT – Henn Timm, TV – Taavi Virro, TM – Tõnu Möls, MH – Marina Haldna, RJ – Rein Järvekülg.

1. INTRODUCTION

As defined in the Water Framework Directive (2002), hydromorphology is the physical characteristics of the shape, boundaries and content of a water body. Alteration of hydromorphology by human activities (e.g. damming, channelization, urbanization, drainage) poses a significant threat to habitat quality and in turn to riverine communities (Poff et al., 1997; Bunn & Arthington, 2002; Santucci et al., 2005; Horsák et al., 2009; Navarro-Llácer et al., 2010; Kennedy & Turner, 2011). The most conspicuous human influence modifying flow velocity and hydromorphological conditions in running waters is damming. In this process part of the lotic ecosystem is transformed into lentic one. The direct impacts of damming are reduction in river flow and increase of sedimentation upstream of the dam (Petts, 1984; Poff & Zimmerman, 2010). At the same time, water velocity increases immediately downstream. Dams can also be formed as a result of the action of natural geological forces or the activity of beavers, which will cause significant changes in the stream biota, particularly upstream (Sillliman et al., 2007; Arndt & Domdei, 2012; Pliūraite & Kesminas, 2012). The effects of dams on the biota depend on the size, age and construction type of dams. Below-dam water often has different temperature and hydrochemical characteristics, compared to normal lotic conditions. If water is released from the near-bottom layer of the reservoir, it is usually cold and oxygen-depleted but nutrient-rich. On the contrary, the water released from the near-surface layer has usually higher temperature than the water downstream (Petts, 1984; Lessard & Hayes, 2003). A well-known issue is the negative effect of dams on migratory fishes. Impoundments can block the way upstream and thus contribute to the decline and even extinction of species that depend on longitudinal movements (Porto et al., 1999; Liermann et al., 2012). Less is known about how the stream biota is affected by changed water velocity and bottom's character.

Channelization is another worldwide threat to stream biodiversity (Rosenberg et al. 2000; Nakamura & Yamada, 2005; Horsák et al., 2009). It results in a temporary increase of flow velocity and flooding, while reduced discharge occurs most of the time. Natural pool-riffle sequences, which provide shelter for fish and macroinvertebrates, are lost. These streams have little or no stable structure in the channel, have few or no meanders or pools, and have no native riparian vegetation to shade the channel and buffer the stream from adjacent human activities (Maxted et al., 2000; Nakano et al., 2008). The effects of channelization on the stream biota depend on the total length of modified reaches, on the proportion of unmodified reaches and on recovery time. The stream biota may recover more slowly in impounded areas than in channelized areas, due to complete loss of normal flow (Hortle & Lake, 1982; Smiley & Dibble, 2008). Channelization may also have long-term negative effects due to decreased habitat diversity (Horsák et al., 2009).

Excessive **water abstraction** from streams, widespread in areas with a warm and dry climate, has much less importance in cooler regions, compared to damming and channelization. The possible effects of it were not estimated in this study.

Benthic macroinvertebrates are small bottom-living animals, visible by naked eye. Their taxonomic composition has been widely used as an indicator of running water pollution by organic, acidic or toxic pollutants (Rosenberg & Resh, 1993). In comparison to fishes or macrophytes, macroinvertebrates stand out with high species number (e.g. > 400 bioindicators in Estonian waterbodies; Timm & Vilbaste, 2010) and are easy to collect. They are widely distributed (occur also in canopied areas, underground and upstream of steep barriers). Therefore, the probability to obtain erroneous results because of the incidental absence of some species is relatively low. Macroinvertebrates are by far the most commonly used group for use in assessing freshwater quality (Rosenberg & Resh, 1993; Cranston et al., 1996). They are also considered a necessary measure of biological quality of freshwaters according to the Water Framework Directive (2002). As damming has a significant negative effect on the chemical and physical elements of streams, it consequenty leads to changes in the macroinvertebrate community (Pozo et al., 1997; Ahearn et al., 2005; Takao et al., 2008). For example, flow fluctuation caused by power stations disturbs macroinvertebrates which in turn respond with lower biodiversity (Cortes et al., 1998; Bruno et al., 2016). It also disrupts colonization of many macroinvertebrates, causing lower taxa richness (Fisher & LaVoy, 1972; Munn & Brusven, 1991). High level periods have a significant negative effect on the diversity of macroinvertebrates in channelized sections compared to natural ones (Negishi et al., 2002).

Biological quality is a measure of the condition of a waterbody relative to the requirements of one or more biotic groups (such as aquatic flora, macroinvertebrates or fishes). In terms of the Water Framework Directive (2002), these groups are called biological elements. Many countries have developed tools to assess the biological quality of streams on the basis of macroinvertebrates. Some use multivariate assessment approaches, some use multimetric indices (e.g. Dahl & Johnson, 2004; Ofenböck et al., 2004; Pinto et al., 2004; Vlek et al., 2004). However, most of the calculation methods focus on organic pollution or acidification, only few reflect hydromorphological modifications (Balestrini et al., 2004; Lorenz et al., 2004). During the recent decades, hydrochemical pollution of streams has been significantly reduced in Western Europe. Instead, hydromorphological modification, considered earlier as a second-rate disturbance after hydrochemical impacts, is now recognized as a primary adverse factor for the stream biota, including macroinvertebrates (Feld, 2004; Lorenz et al., 2004). In Europe, there are currently two indication systems to estimate the direct effects of hydromorphological degradation on stream macroinvertebrates: one used in Germany (Schmedtje & Colling, 1996) and the other, in Great Britain (Extence et al., 1999). Similar tools are also available for British Columbia, Canada (Armanini et al., 2011), New Zealand (Greenwood et al., 2016) and South Korea (Kong, 2016).

Estonia (together with Latvia and Lithuania) forms a separate Baltic province ecoregion in terms of the Water Framework Directive. This province is bordered with the Eastern plains in the East, the Fenno-Scandian shield in the north and the Central plains in the west. Estonia seems to be a suitable area to study the effects of different hydromorphological disturbances on macroinvertebrates, for the following reasons: (1) existence of a large number of differently hydromorphologically disturbed waterbodies, (2) lack of appropriate information for this region, as well as for the neighboring areas and (3) location of the Baltic province on the border of three other large ecoregions, which enables to test the results within the surrounding areas with a similar species list.

A multimetric index was developed to estimate the effects of organic pollution and general degradation on stream macroinvertebrate communities in Estonia (Status classes..., 2009; Timm & Vilbaste, 2010). However, it is not clear whether the included metrics (different kinds of taxon richness, Shannon diversity etc.) reflect hydromorphological disturbances appropriately. None of the specific hydromorphological indication systems listed above is applicable to the Baltic conditions: they contain too many missing or redundant species in their indicator lists. Moreover, calculation of the British score on the basis of the local material was not possible because of the incompatibility of sampling procedures.

According to the Estonian Environmental Register, there are more than 1000 dams, including destroyed objects, on Estonian running waters. Most of them are lower than 5 m and are used mainly for recreation and/or irrigation. As the hydroenergetic potential of Estonian streams is low because of the to low gradient of most stream channels, the number of hydroelectric power stations is also small. In 2011, there were only 47 working stations and watermills with a total capacity of only 8.09 MW (Raesaar, 2005).

Purposeful excavation of ditches on the current territory of Estonia started already in the 1820s. Stream channelization works became particularly intensive in the 1950s (Etverk, 1974). Most small streams were straightened and/or dredged (Tuulmets & Aasalo, 1980). In addition, up to 140,000 km of ditches are found nowadays (Lindström & Koff, 2005). This is 4.5 times more than the total length of all Estonian natural streams. However, woodland ponds and ditches in Estonia were considered species rich and diverse habitats. Although drainage reduces their taxonomic richness, ditches in semi-naturally managed forests can serve as replacement habitat for most taxa (Vaikre et al., 2015).

2. AIMS

The aims of this study were the following:

1) to assess whether and how much the macroinvertebrate communities were changed in the hydromorphologically modified (dammed or channelized) running waters compared to the streams in near-natural conditions (papers **I, III, IV**). The communities were characterized a) by indicator species, b) by biological quality (in terms of the current national multimetric estimation system);
2) to develop a special index, on the basis of macroinvertebrates, for assessment of only hydromorphological disturbances (paper **II**);
3) to compare the ability of the old and new indices to reflect relationships between hydromorphological changes and macroinvertebrates (all papers).

3. MATERIAL AND METHODS

3.1. Study area and sampling sites

Estonia is a small country (area 45,200 km^2) with a flat landscape (mean altitude 50 m above sea level), situated on the eastern shore of the Baltic Sea, with a prevailing altitude lower than 200 m. It belongs to the area of mixed forests of the temperate zone, bordering the taiga. In comparison with the southern areas, it is characterized by extensive areas of raised bogs and forests (Raukas & Rõuk, 1995). There occur more than 7,300 running waters, with a total length of ca 31,000 km (Loopmann, 1979).

When selecting of the modified sampling areas, the availability of appropriate reference areas, as well as their accessibility for researchers were taken into consideration. As a rule, the reference areas were located not farther than 2 km from the modified areas (to ensure that both were of the same stream size), and were situated upstream (to avoid self-disturbance). In the pairwise study (paper **IV**), the areas with obvious evidence of channelization were first chosen using maps and their suitability was then checked in the field. The reference sites were located in near-natural areas without hydrochemical pollution and/or hydromorphological (human- of beaver-induced) disturbances.

3.2. Sampling

The macroinvertebrate sampling sites included in the papers **I**–**IV** are shown in Fig. 1. The samples were collected from shallow areas (depth < 1 m) in spring after the highwater period (papers **I**, **III**, **IV**) or partly in late autumn (paper **I**). Summer was excluded to avoid the period when many heterotopic insects have left the water environment. The areas with direct hydrochemical pollution were avoided, to focus on hydromorphological changes only. A standard handnet with an edge length of 25 cm and a mesh size of 500 μm (European..., 1994) was used. Altogether six subsamples were taken from each site: five subsamples collected from the most typical bottom (together 1.25 m^2), and a qualitative sample which included different available habitats (Medin et al., 2001). Most of the samples from 1985–2000 (paper **II**) were qualitative and a significant part of them were collected also in summer. The collected animals were fixed, together with sieving residues with 96% ethanol and transported to the laboratory for analysis. The animals were identified to the species or to the genus level, according to Johnson (1999). Chironomids, oligochaetes, water mites and other organisms, whose identification required higher magnification, were not determined further.

At each site, flow velocity and composition of the bottom substrate were estimated visually on a four-point scale: 0 – no flow and/or muddy bottom, 1 –

slow flow (< 0.2 m s^{-1}) and/or sandy bottom, 2 – fast flow (> 0.2 m s^{-1}) and/or sandy-stony bottom, 3 – very fast flow (0.2 m s^{-1}) and/or stony bottom.

For papers **III** and **IV** (pairwise study), water temperature, dissolved oxygen (O_2), oxygen saturation (O%), pH and conductivity were measured in the field.

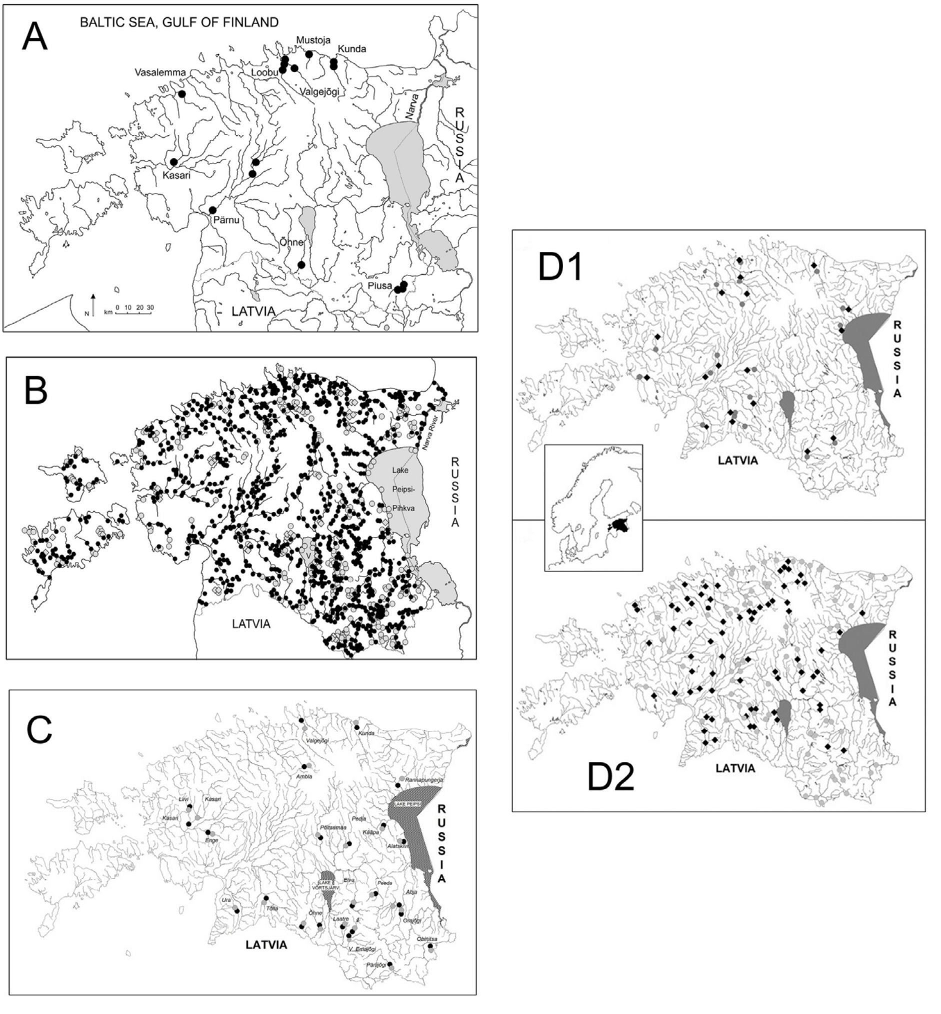

Figure 1. Study area. A – paper **I** (16 dams, 32 sites in 2005–2006), B – paper **II** (3,282 sites in 1985–2009; including also the lake littoral areas), C – paper **III** (24 dams, 72 sites in 2009–2010), D1 – paper **IV,** pairwise dataset (24 channelized streams, 48 sites in 2009–2010), D2 – paper **IV**, background dataset (73 channelized streams and 73 unchannelized streams in 2000–2010).

3.3. Estimation of biological quality

To assess the biological quality of running waters, a national multimetric index, based on five components, was used (Status classes..., 2009). These indices were the following: total taxon richness T (indicating total biological diversity); Ephemeroptera, Plecoptera and Trichoptera larvae taxon richness EPT (indicating pollution-sensitive taxon diversity; Lenat, 1988); Shannon diversity H´ (indicating how many different species there are in a dataset, and simultaneously taking into account how evenly the individuals are distributed among those species); Average Score Per Taxon ASPT (mean sensitivity of taxon; Armitage et al., 1983); and Danish Stream Fauna Index (DSFI) (indicating the level of organic pollution; Skriver et al., 2000). The H´ was calculated on the basis of five area-based subsamples only. For the other metrics, the qualitative subsample was also included. The corresponding table of the biological quality classes (Appendix) was used to attribute quality levels to all five indices. All results of high quality were assigned five points, the values of good quality, four points, the values of moderate quality, two points, and the values of poor and bad quality, zero points. The difference between good level and moderate level was intentionally emphasized in order to underline the principal difference between them in terms of the Water Framework Directive (2002). According to the Directive, the European member states must protect and improve their surface waters to achieve at least good ecological status. Instead, the difference between poor level and bad level was ignored, as they had no actual difference. Multimetric quality (MMQ) was then calculated by adding up the corresponding points. Hence, the sum 23−25 was considered to indicate high quality, 18−22, good, 10−17, moderate, 6−9, poor and < 6, bad quality.

The values of all indices and the estimates of multimetric quality were then divided by their corresponding reference values (5 for each single index and 25 for the multimetric quality, respectively), resulting in observed/expected ratios, called also Ecological Quality Ratios (**EQR**). The EQR-s are universal values that enable to compare different metrics. The acceptable range for the boundary between high quality and good quality in European streams is 0.84 – 0.94 and the range between good quality and moderate quality is 0.64 – 0.75 (Van de Bund, 2009). For Estonian streams, these boundaries were classified as follows: high > 0.9, good 0.7−0.9, moderate 0.4−0.7, poor and bad < 0.4 (Timm & Vilbaste, 2010).

The MESH index (developed with the participation of the author), is based on the affinities of macroinvertebrate taxa to flow velocity and bottom substrate (paper **II**). The corresponding quality levels and thus the EQR values of MESH are not yet available.

3.4. Data analysis

In paper **I**, the effect of damming on the structure of the macroinvertebrate community and biological quality was studied for two types of reservoirs: 1) with a large amount of accumulated fine sediments, and 2) with hard bottom; and for the corresponding below-dam areas. Generalized linear models implemented in the SAS Genmod procedure (SAS 9.1.3 Help and Documentation, 2004) were used. In calculations, the differences between the sampling sites were partly eliminated by using repeated measures analysis as realized in the Repeated clause of the Genmod procedure. Comparison of the biological indices was performed in a similar way but, instead of the Genmod procedure, the SAS Mixed procedure of mixed-type analysis of variance was used. Following multiple comparisons (183 taxa, 24 indices), significance level α was corrected in the Bonferroni sense using $\alpha = 0.0005$ when comparing the taxa and $\alpha = 0.002$ when comparing the indices.

In paper **II**, a new index was developed to assess the hydromorphological quality of Estonian surface waters, based on the taxonomic composition of macroinvertebrate (**MESH** – **M**acroinvertebrates in **E**stonia: **S**core of **H**ydromorphology). Both flow velocity and bottom type were estimated visually using a four-level scale. The lowest flow velocity and the softest bottom were coded with "0", the fastest flow and the hardest bottom, with "3". Combinations of the values of Flow Score and Bottom Score were named Flow-Bottom Score, because of a highly significant correlation between them. This score was then calculated for 690 macroinvertebrate taxa, adjusting the scores over the occurrence of taxa in different habitats. The taxa were analyzed to calculate informativeness (IG) with respect to the habitats using the Kullback-Liebler difference (Renyi, 1970). The statistical significance of IG was modelled using the SAS IML procedure, repeating the IG calculation 200,000 times. In total, 394 taxa were qualified as indicators. Finally, all indicators were divided into clusters again, with Flow-Bottom Score values of 0 (muddy littoral), 1 (sandy littoral), 2 (slow-flowing stream, or stony littoral), or 3 (fast-flowing stream). The MESH is the average Flow-Bottom Score consisting of the sum of the individual scores of all indicator taxa in a sample divided by the number of the indicator taxa in the sample.

In paper **III**, the impact of damming (above-dam versus below-dam versus undisturbed areas) and in paper **IV**, the effect of channelization (channelized versus undisturbed areas) on macroinvertebrates and stream physiochemical parameters was estimated. In both cases, the data were analyzed using the R (R Development..., 2009) or Statistics 8.0 software (R Development Core Team, Vienna, Austria, 2009). A general linear model was used by comparing the contrasts of three-factor level (above-dam, below-dam, undisturbed). The effect of channelization on the continuous variables of macroinvertebrates and on physicochemical parameters was assessed using one-way analysis of variance (ANOVA). For the categorical variable (Danish Stream Fauna Index), non-parametric Kruskal-Wallis test or Mann-Whitney U test were employed. For comparison of the metrics, the EQR-s were used. In both papers, the Bonferroni p-value was adjusted according to the number of tests. In addition, Indicator Species Analysis (Dufrêne & Legendre, 1997) was used in paper **IV**, to detect indicator species for the channelized stream sections.

To generalize the effects of damming and channelization on biological and hydromorphological indices, the data from papers **I**, **III** and **IV** were combined and analyzed separately in the Thesis. The residuals of the macroinvertebrates metrics were compared for deviation from a normal distribution using the Shapiro-Wilk's test. In most cases, the one-way analysis of variance (ANOVA) was used. The Danish Stream Fauna Index and MESH were examined by the non-parametric Kruskal-Wallis test, followed by multiple comparison of mean ranks. The critical Bonferroni p-value was 0.007. The Kruskal-Wallis non-parametric test was run in Statistica 8.0 (StatSoft, Inc., 2011) and ANOVA was performed with the software R 3.2.4 (R Development Core Team, Vienna, Austria, 2016).

4. RESULTS AND DISCUSSION

4.1. Taxonomic composition of macroinvertebrates

4.1.1. Effects of damming

In the sediment-rich reservoirs, some insect larvae (Chironomidae, lentic ephemeropteran *Cloeon dipterum*), crustaceans *Asellus aquaticus*, *Gammarus pulex*, and oligochaetes were the most abundant taxa. Except for the highly mobile *G. pulex*, they all usually inhabit slow-flowing or standing waters. The larvae of several other insects (among them the rheophilic ephemeropteran *Baetis rhodani* and Simuliidae) and *G. pulex* dominated in the below-dam reaches of the sediment-rich reservoirs. In the hard-bottomed reservoirs, the riffle beetle *Elmis aenea*, oligochaetes, chironomid larvae and *G. pulex* were the most abundant. In the corresponding below-dam reaches, Chironomidae, larvae of the filtering caddisfly (*Hydropsyche pellucidula*) and another riffle beetle, *Limnius volckmari*, prevailed (paper **I**). Similarly to this study, Shao et al. (2008) considered chironomids and oligochaetes typical inhabitants of reservoirs. Boles (1981) noted that Simuliidae, *Baetis* and Chironomidae were usually found in below-dam areas, owing to abundant food supply.

In the larger damming-based dataset, the above-dam taxa were similarly usually lentic (paper **III**). The typical representatives were leeches, snails and water mites, but also some mayfly, damselfly, and caddisfly larvae. The below-dam taxa often included numerous filtrators (such as pea clams, caddisfly and Simuliidae larvae), typical of natural lake outflows. In turn, the taxa of the undisturbed sites included many rheophiles, such as the snail *Theodoxus fluviatilis*, the crustacean *Gammarus pulex*, several mayfly, stonefly and caddisfly larvae; riffle beetles, and the water bug *Aphelocheirus aestivalis.* However, the rare mayfly species *Arthroplea congener* was only found in lentic reservoirs. Changes in the functional feeding groups above and below dams can be primarily explained with differences in food supply (Spence & Hynes, 1971). On the basis of the current study, hydromorphological conditions (such as flow velocity and bottom substrate type) are of not less importance than food.

4.1.2. Effects of channelization

According to Indicator Species Analysis, only two taxa (the caddisfly larvae of *Limnephilus* sp. and the leech *Glossiphonia complanata*) were significantly ($p<0.05$; uncorrected for multiple comparisons) associated to channelized sites in the small (pairwise) dataset (paper **IV**). Four taxa (*Elmis aenea*, mayfly *Heptagenia sulphurea* larvae, and two species of caddisfly larvae − *Cheumatopsyche lepida* and *Rhyacophila* sp.) were significantly associated with near-natural (reference) areas. In the large (background) dataset, four taxa (the dipteran family Ceratopogonidae, and three species of caddisfly larvae:

Limnephilus flavicornis, *L. lunatus* and *Ironoquia dubia*) were significantly associated with channelized sites. Nine taxa were significant indicators of the unchannelized sites: seven species of caddisfly larvae (*Hydropsyche pellucidula*, *Sericostoma personatum*, *Lepidostoma hirtum*, *Cheumatopsyche lepida*, *Ithytrichia lamellaris*, *Odontocerum albicorne*, *Hydropsyche siltalai*), a whirligig beetle larva (*Orectochilus villosus*), and a cranefly larva (*Antocha* sp.). The indicators of the channelized sites were mostly typical of slow-flowing waters (according to MESH, Paper **II**), while the indicators of the reference sites were usually found in fast-flowing reaches.

4.2. Biological, hydromorphological and hydrochemical quality

To summarize the analyses, the datasets of the papers **I**, **III** and **IV** were combined. Table 1 and Fig. 2 comprise the mean values of the biological quality metrics and their EQR-s for the four habitats: above-dam (reservoir), below-dam, channelized and reference. In Table 2, the EQR values are compared pairwise by either ANOVA or the Kruskal-Wallis test.

Table 1. Metrics of biological quality for the hydromorphologically modified (above-dam, below-dam and channelized) and for the reference habitats. Bold letters indicate arithmetic means, the Ecological Quality Ratio (EQR) values are in brackets. The EQR quality levels are the following: high > 0.9, good 0.7–0.9, moderate 0.4–0.7, poor and bad < 0.4. T – total taxon richness, EPT – taxon richness of Ephemeroptera, Plecoptera and Trichoptera larvae, DSFI – Danish Stream Fauna Index, ASPT – Average Score Per Taxon, H´ – Shannon diversity, MMQ – multimetric quality, MESH – score of hydromorphology.

	Arithmetic mean			
Metric	Above-dam (n=42)	Below-dam (n=42)	Channelized (n=91)	Reference (n=115)
T	**32.1** (1.20)	**35.0** (1.09)	**30.5** (1.08)	**35.0** (1.19)
EPT	**11.5** (0.81)	**16.3** (1.07)	**12.6** (0.95)	**16.2** (1.16)
DSFI	**4.90** (0.70)	**6.21** (0.89)	**5.58** (0.80)	**6.53** (0.93)
ASPT	**5.49** (0.82)	**5.96** (0.88)	**5.51** (0.84)	**6.17** (0.92)
H´	**2.68** (0.91)	**2.64** (0.99)	**2.49** (0.94)	**3.07** (1.08)
MMQ	**16.6** (0.67)	**20.4** (0.82)	**19.4** (0.77)	**23.2** (0.95)
MESH	**1.77**	**2.50**	**2.47**	**2.59**

Total taxon richness (**T**) was quite similar for all habitats. There were no significant differences in T between any modified habitats or reference areas. Nevertheless, the mean values of T for the reference and below-dam habitats were the highest (Tables 1–2). The mean EQR (observed/expected ratio) of T revealed also high quality for all habitats. Thus, the current study does not support total taxon richness as an appropriate tool to assess hydromorphological changes. At the above-dam sites, the rheophilic species inhabiting this area earlier had probably been replaced by limnophilic species (as indicated by MESH, see below).

In the channelized reaches, natural species had also been replaced by other, more tolerant natural taxa by stream drift and other ways of the self-recovery of the habitat. Like in this study, hydromorphological alteration was not followed by a substantial decline in whole-community richness in several streams of the Netherlands, Germany and Poland (Feld, 2004). Channelization of boreal streams for timber transport did not alter hydromorphological conditions sufficiently to have a strong impact on the taxon richness of macroinvertebrates in Finland (Turunen et al., 2016). However, several authors reported a significant decrease in taxon richness in channelized streams (Negishi et al., 2002; Horsák et al., 2008; Pliūraite and Kesminas, 2010).

The number of sensitive taxa (**EPT**) and the index of organic pollution (**DSFI**) were significantly lower for the reservoirs and channelized reaches, compared to the reference areas. However, this relationship was not significant for the below-dam sites. The mean EQR of EPT indicated good quality for the reservoirs and high quality for the other habitats, being only slightly lowered for the channelized reaches. At the same time, the EQR of DSFI was moderate for the reservoirs, good for the below-dam and channelized habitats, and high only for the reference areas. Conditions for pollution-sensitive macroinvertebrates were not significantly deteriorated in the above-dam areas in case mud accumulation was low (paper **I**). At the same time, in the below-dam areas, disturbance to sensitive species might have been masked by fast flow. Even some pollution-tolerant species were sensitive to low water velocity in the reservoirs (paper **III**). A decreased EPT for the dammed areas was also observed in streams of Illinois, USA, due to degraded habitat and/or lowered water quality (Santucci et al., 2005). The structure of the macroinvertebrate community downstream a dam in Ontario (Canada) seemed to suffer for stress similar to mild organic pollution (Spence & Hynes, 1971). The channelized sites in the current study had significantly lower EPT and DSFI compared those in the reference areas (paper **IV**).

Mean taxon sensitivity (**ASPT**), Shannon diversity (**H′**) and multimetric quality (**MMQ**) were all significantly lower in the three modified habitats compared to the reference area. The EQR of ASPT revealed high quality for the reference area and good quality elsewhere (however, the lowest value was observed for the reservoirs). The EQR of Shannon diversity was high for all habitats. Davy-Bowker & Furse (2006) and Friberg et al. (2009) also found that ASPT was correlated significantly negatively to channel modification. Rabeni (2000) considered diversity indices as the most sensitive to habitat changes for stream macroinvertebrates. In this study, the mean EQR of Shannon diversity (**H′**) indicated high biological quality for all habitats, although the lowest value was observed for the above-dam habitat, and the highest quality, for the reference area.

The EQR of **MMQ** (biological quality on the basis of the five above indices) was the lowest for the reservoirs (moderate), followed by the channelized (good), below-dam (good) and reference habitats (high) (Table 1). The effect of insensitive total taxon richness was surpassed by the effects of the other four sensitive indices.

The MESH was significantly lower for the reservoirs compared to the reference areas, as well as to the other habitats. For the below-dam and channelized habitats with fast flow and hard bottom, it was not significantly different from that for the reference areas (Fig. 2, Table 2). Nevertheless, in the dataset used in paper **III**, a significant difference in MESH between the below-dam and the reference areas was observed. At the same time, all hydrochemical and hydrophysical parameters (water temperature, dissolved oxygen (O_2), oxygen saturation (O%), pH and conductivity) were highly similar among these three habitats. Thus, some advantage of macroinvertebrate quality indicators over commonly approved abiotic parameters for streams was ascertained.

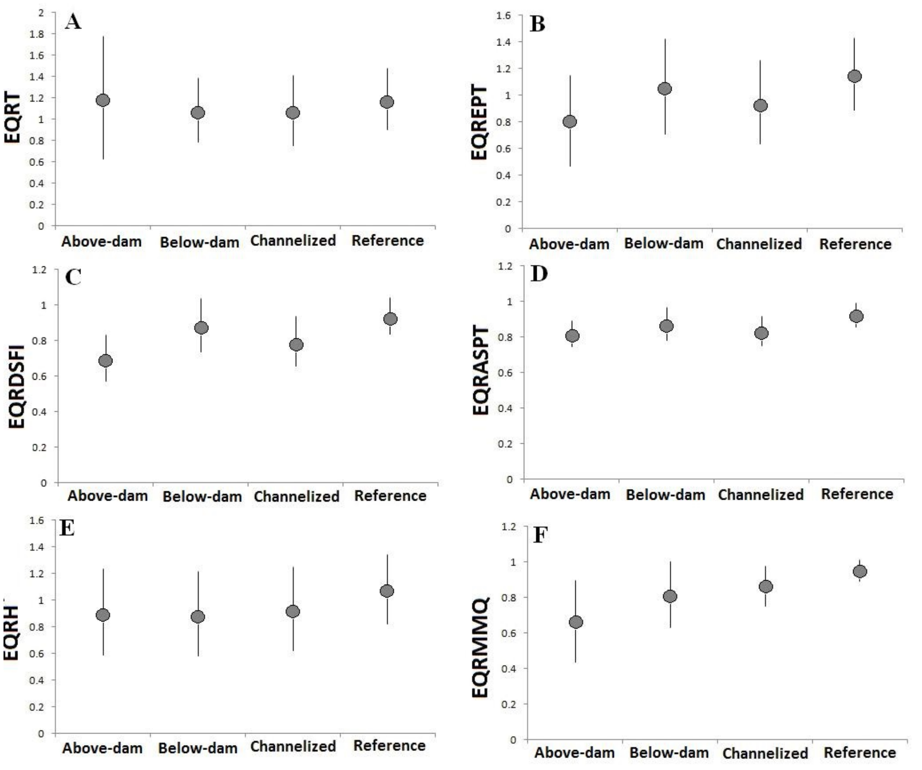

Figure 2. Comparison of the EQR values of the quality metrics (mean ± SD). T – total taxon richness, EPT – taxon richness of Ephemeroptera, Plecoptera and Trichoptera larvae, DSFI – Danish Stream Fauna Index, ASPT – Average Score Per Taxon, H´ – Shannon diversity, MMQ – multimetric quality.

Table 2. Comparison of Ecological Quality Ratios (EQR) of the metrics between different hydromorphological habitats (by ANOVA and Kruskal-Wallis (*) tests). T – total taxon richness, EPT – taxon richness of Ephemeroptera, Plecoptera and Trichoptera larvae, DSFI – Danish Stream Fauna Index, ASPT – Average Score Per Taxon, H′ – Shannon diversity, MMQ – multimetric quality, MESH – score of hydromorphology. n.s. – not significant. The critical Bonferroni p-value is 0.007.

Metric	p-value					
	Above-dam – Below-dam	Above-dam – Channelized	Below-dam – Channelized	Above-dam – Reference	Below-dam – Reference	Channelized – Reference
EQR-T	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
EQR-EPT	0.001	n.s.	n.s.	<0.0001	n.s.	<0.0001
EQR-DSFI*	<0.0001	0.004	0.003	<0.0001	n.s.	<0.0001
EQR-ASPT	0.004	n.s.	n.s.	<0.0001	0.002	<0.0001
EQR-H′	n.s.	n.s.	n.s.	0.007	0.003	0.002
EQR-MMQ	<0.0001	<0.0001	n.s.	<0.0001	0.0001	<0.0001
MESH*	<0.0001	<0.0001	n.s.	<0.0001	n.s.	n.s.

Although other specific hydromorphological indication systems were not applicable to conditions in the the Baltic region, correlation between scores of the common elements for individual taxa in MESH and the corresponding British index LIFE (Extence et al., 1999) was fair ($p < 0.05$, $r = -0.5987$, $n = 252$). After transforming the verbal categories of rheophility into the corresponding six classes after Schmedtje and Colling (1996) (ignoring the class "indifferent"), a relatively similar result was obtained ($r = -0.5829$, $n = 271$) (paper **II**).

In relation to hydromorphological stress, the analyzed indices can be arranged into three groups: 1) insensitive (total taxon richness); 2) the lowest value for the reservoirs, the slightly higher value for the below-dam habitat than for the channelized area, the highest value for the reference area (EPT, DSFI); 3) the lowest value for the reservoirs, a similar value for the below-dam and channelized areas, the highest value for the reference areas (ASPT, H′, MESH). Although EPT, ASPT and H′ indicated good or even high quality for hydromorphologically modified habitats, their lowest mean values were always registered for the most degraded (above-dam) areas and the highest values were registered for the reference areas. The high MESH values for the below-dam and channelized habitats indicate that these areas were near-natural in terms of bottom hardness and flow velocity.

5. CONCLUSIONS

Macroinvertebrate communities responded significantly to both main hydromorphological disturbances − damming and channelization − in streams of Estonia. Most macroinvertebrate-based indices of biological quality, belonging to the corresponding national multimetric index, were significantly and negatively influenced both by damming and channelization. Unlike the other tools, a new index (MESH) was specially developed to assess hydromorphological changes. The MESH distinguished reliably the above-dam macroinvertebrate species from those of the other areas but failed to distinguish the species of the channelized habitats and the species of the reference areas. However, the latter difference can be well estimated by other available indices (EPT, DSFI, ASPT and H′). Nevertheless, inclusion of MESH in the national system as a relevant indicator of damming can be recommended, including development of corresponding reference values and quality levels that are in line with the European Water Framework Directive.

SUMMARY

Alteration of hydromorphology as a consequence of human activities (e.g. damming and channelization) poses a significant threat to habitat quality and in turn to riverine communities. Taxonomic composition of benthic macroinvertebrates has been widely used as an indicator of running water quality. Macroinvertebrates are also considered a necessary biological quality measure of freshwaters according to the Water Framework Directive. However, the corresponding metrics have been mostly focused on organic pollution or acidification, and only seldom on hydromorphological modifications. Estonia (together with Latvia and Lithuania) forms a separate Baltic province ecoregion in terms of the Water Framework Directive. Despite the occurrence of a large number of dammed and channelized waterbodies in this region, the effects of these disturbances on macroinvertebrates have almost not been studied. Nor is it not clear whether the metrics included in the Estonian multimetric index of biological quality (total taxon richness T, sensitive taxon richness EPT, organic pollution index DSFI, mean sensitivity of taxon ASPT, and Shannon diversity H′) reflect hydromorphological disturbances appropriately. To clarify this issue, the relationships of these indices with damming and channelization were estimated for four habitats: above-dam, below-dam, channelized, reference. In addition, a new index (MESH), based on the affinities of 394 macroinvertebrate species to flow velocity and bottom type, was developed.

The taxa found at the above-dam sites were usually associated with standing waters. Similarly, significant indicators of channelized stream reaches were typical of slow-flowing waters. The taxa of the below-dam areas often included numerous filter-feeding species, while the taxa of the undisturbed sites included many rheophiles. Total taxon richness was similar for all habitats, as in the modified areas sensitive species had been replaced by tolerant species. However, all other indices (including multimetric estimation MMQ) were significantly negatively influenced by damming and/or channelization. The MMQ was the lowest for the reservoirs (with moderate biological quality), followed by the channelized (good quality), below-dam (good quality) and reference habitats (high quality). In conclusion, macroinvertebrate communities responded significantly to both main hydromorphological disturbances − damming and channelization − in streams of Estonia.

SUMMARY IN ESTONIAN

Inimtekkeliste hüdromorfoloogiliste muutuste mõju vooluvete seisundile suurselgrootute järgi Eestis (Euroopa, Balti ökoregioon)

Inimesed on muutnud väga paljude vooluveekogude hüdromorfoloogiat: voolukiirust, põhja iseloomu ja voolusängi kuju. Sellised muutused on nende veekogude elustikku sageli oluliselt mõjutanud. Kõige silmapaistvam mõju on paisutamine. Ülalpool paisu asuvas jõelõigus on voolukiirus pidurdatud, mis soodustab muda kogunemist; vahetult allpool paisu aga see-eest tugevasti suurendatud. Paisutamise mõju vee-elustikule sõltub paisu kõrgusest, vanusest ja ehituslikest eripäradest. Mõned loomad (näiteks siirdekalad) ei pruugi paisudest mööda pääseda neile elutähtsatesse piirkondadesse. Vähem teatakse sellest, kuidas elustikku mõjutavad muutunud voolukiirus ja/või põhja iseloom.

Õgvendamise käigus kaevatakse kogu vooluveekogu või mõni selle osa sirgeks. Tulemuseks on voolukiiruse ja põhja iseloomu ühtlustumine ning vooluhulga sesoonse stabiilsuse vähenemine. Enamasti eemaldatakse õgvendustööde käigus ka looduslik kaldataimestik (sh mets), mis varem jõesängi varjutas ja oli oluliseks orgaanilise aine allikaks vees.

Suurselgrootud on palja silmaga nähtavad, veekogude põhjal, taimedel, setete sees või veepinnal elavad loomad. Neid on veekogude seisundi indikaatoritena kogu maailmas palju kasutatud, sest nad reageerivad ennustatavalt mitmesugusele inimtegevusele, eriti orgaanilisele ja happelisele veereostusele. Ka Eestis on vastav, Euroopa Veepoliitika Raamdirektiivi nõuetest tulenev indikatsioonisüsteem välja töötatud. See on samuti suunatud pigem orgaanilise reostuse ja/või tuvastamata stressiallikate mõju hindamisele, mitte hüdromorfoloogilistele muutustele. Samas, ehkki väga suur osa Eesti vooluvetest on paisutatud või õgvendatud, pole seisundi hindamise mõttes uuritud, kas ja kuidas suurselgrootud sellele reageerivad.

Praeguse töö eesmärgid olid järgmised:

1) hinnata paisutamise ja õgvendamise mõju vooluvete seisundile, kasutades senist suurselgrootutel tuginevat hindamissüsteemi,
2) töötada välja uus indeks just hüdromorfoloogiliselt muudetud vooluvete seisundi hindamiseks,
3) võrrelda varasemate indeksite ja uue indeksi tulemuslikkust paisutatud ja õgvendatud vooluvete seisundi hindamiseks.

Paisutamise ja õgvenduse mõju uurimiseks võeti suurselgrootute proovid vooluvetest enamasti kevadel: pärast suurvee taandumist, kuid enne, kui suurem osa putukatest oleks jõudnud veest välja lennata. Materjal koguti nelinurkse standardkahvaga jalaproovide ja kahvatõmmete abil. Iga proov koosnes 1,25 m^2 suurusest pindalapõhisest osast ning kvalitatiivsest osast. Et keskenduda just hüdromorfoloogilistele muutustele, välditi otsese hüdrokeemilise reostusega alasid.

Praegu Eestis kehtiv vastav seisundisüsteem koosneb viiest indeksist: T (üldine taksonirikkus), EPT (tundlike taksonite rikkus), DSFI (orgaanilise reostuse tase), ASPT (taksoni keskmine tundlikkus) ning Shannoni erisus. Iga indeksi seisundiväärtus annab kindla arvu punkte, mis summeeritult moodustavad koondhinnangu MMQ. Kohapealse materjali põhjal loodud uus indeks (MESH) tugineb Eesti liikide tundlikkusel voolukiirusesse ning põhja iseloomu. Seega peaks ta eeldatavasti sobima nii paisutamise kui õgvendamise mõju hindamiseks suurselgrootute taksonoomilisele koosseisule.

Eriti selgelt reageerisid suurselgrootud paisjärvede mudastumisele, kus reofiilsed liigid olid asendunud seisuveeliste liikidega. Ülalpool paise olid muuhulgas väga arvukad näiteks seisuveelise ühepäevikulise *Cloeon dipterum* vastsed ning vesikakand *Asellus aquaticus*. Allpool paise, kus voolukiirus suur, aga vees leidub palju paisjärvedes moodustunud hõljumit, olid sagedad voolulembesed liigid, kelle seas palju filtreerijaid (teiste seas näiteks kihulaste (*Simuliidae*) või ehmestiivalise *Hydropsyche pellucidula* vastsed). Õgvendatud jõelõike eelistasid keskmise või madala reostustundlikkusega või mitte eriti voolulembesed liigid (näiteks lamekaan *Glossiphonia complanata*, habesääsklaste (*Ceratopogonidae*) vastsed, ehmestiivalise *Limnephilus flavicornis* vastsed). Hüdromorfoloogiliselt rikkumata kohtades aga olid tavalised kõrge reostustundlikkuse ning voolulembesusega liigid (näiteks vesiking *Theodoxus fluviatilis*, kärestikulutikas *Aphelocheirus aestivalis*, paljude ühepäevikuliste, kevikuliste ja ehmestiivaliste vastsed).

Paisutamine ja õgvendamine mõjutasid enamikku võrreldud seisundiindeksitest (välja arvatud üldine taksonirikkus T, kuid kaasa arvatud uus indeks MESH). Paisjärvedes oli seisund suurselgrootute järgi kas oluliselt madalam või vähemalt absoluutväärtuselt kehvem kui muudes uuritud elupaikades (allpool paise, õgvendatud, mõjutamata alad). Nii allpool paise kui õgvendatud lõikudes oli koondseisund viie indeksi põhjal paisjärvedega võrreldes oluliselt parem, kuid mõjutamata aladega võrreldes oluliselt kehvem. Töö aluseks olevate artiklite põhjal kombineeritud andmebaasi alusel oli suurselgrootute keskmine koondseisund senise hindamissüsteemi järgi järgmine: paisjärvedes kesine, õgvendatud lõikudes ja allpool paise hea, ning mõjutamata aladel väga hea. MESH võimaldas usaldusväärselt hinnata paisjärvede mõju, mõnikord paisualuste lõikude mõju, kuid mitte õgvenduse mõju suurselgrootutele.

Paisutamise suhtes osutusid suurselgrootud isegi tundlikumaks kui mõned tavapärased hüdrokeemilised ja -füüsikalised parameetrid (temperatuur, hapnikusisaldus, pH, elektrijuhtivus). Viimaste kevadel mõõdetud väärtused ei erinenud paisjärvede, paisualuste ning mõjutamata alade vahel oluliselt, samas kui loomastiku järgi sai neid elupaiku eristada. Enamik suurselgrootute põhjal koostatud seisundiindeksitest (nii need, mida kasutati seni hüdrokeemilise seisundi või tuvastamata mõjude hindamiseks, kui otseselt hüdromorfoloogiliste mõjude hindamiseks loodud MESH) osutusid Eesti vooluvete paisutamise ja/või õgvenduse suhtes oluliselt tundlikeks. MESH on soovitatav kaasata kehtivasse hindamissüsteemi kui paisutamise indikaator, kehtestades talle ühtlasi seisundiklasside piirid.

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APPENDIX

Reference conditions and quality levels for macroinvertebrate indices in Estonian streams (according to Status classes..., 2009; adapted). R – reference, H – high, G – good, M – moderate, P – poor and B – bad.

Metric	Catchment area, flow velocity and bedrock	R	H	G	M	P or B
Total taxon richness	<100 km^2, fast-flowing	29	>26	23–26	17–22	<17
Total taxon richness	<100 km^2, slow–flowing	18	>16	14–16	11–13	<11
Total taxon richness	100–1,000 km^2, fast–flowing	35	>32	28–32	21–27	<21
Total taxon richness	100–1,000 km^2, slow–flowing	29	>26	23–26	17–22	<17
Total taxon richness	>1,000 km^2	33.5	>30	27–30	20–26	<20
EPT	<100 km^2, fast–flowing	13	>12	10–12	8–9	<8
EPT	<100 km^2, slow–flowing	9	>8	7–8	5–6	<5
EPT	>100 km^2	16,5	>15	13–15	10–12	<10
Shannon diversity	<100 km^2, limestone	2.4	>2.1	1.9–2.1	<1.9–1.4	<1.4
Shannon diversity	<100 km^2, sandstone and >100 km^2	3	>2.7	2.4–2.7	<2.4–1.8	<1.8
ASPT	<100 km^2, slow–flowing	6.1	>5.5	4.9–5.5	<4.9–3.7	<3.7
ASPT	<100 km^2, fast–flowing	6.6	>5.9	5.3–5.9	<5.3–4	<4
ASPT	>100 km^2	6.9	>6.2	5.5–6.2	<5.5–4.1	<4.1
DSFI	<10,000 km^2	7	6–7	5	4	<4

PUBLICATIONS

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Käiro, K., Timm, H. & Virro, T. (2009). Differences between stream reservoirs and lakes, according to littoral macroinvertebrates (poster presentation). A benthic perspective to restoration, mitigation and adaptation of freshwaters: Nordic Benthological Meeting VII. Tartu, Estonia, September 7–10 2009.

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