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ASSESSMENT OF SPATIAL AND TEMPORAL CHANGES OF ECOLOGICAL STATUS OF STREAMS IN CZECHIA: A GEOGRAPHICAL APPROACH

LANGHAMMER, J., MATOUŠKOVÁ, M., KLIMENT, Z. (2013): Assessment of spatial and temporal changes of ecological status of streams in Czechia: a geographical approach. Geografie, 118, No. 4, pp. 309–333. – This paper presents results obtained through research on the changes in the ecological status of streams in Czechia and discusses the potential of a geographical approach to this type of research. The research addresses the key aspects of the ecological status of streams: changes in the quality of surface water, erosion and the hydromorphological condition of streams in various environments and at different spatial scales. The methodological aspects of the research are discussed in relation to the requirements and standards stemming from the application of the EU Water Framework Directive. The results show that changes in the ecological status of streams are complex in their character and spatial impact. Intensive long-term changes of streams and their pollution levels appear in heavily populated areas with industrial activity and in agricultural areas with small streams. Analyses of case studies indicate an increase in the spatial differentiation of changes in the ecological status of streams. The changes in the ecological status of streams are determined by the intensity of anthropogenic pressure, spatial distribution of the principal factors, connectivity of the systems and physiographic properties of landscape. The findings from studies conducted at different spatial scales and in varying geographical conditions point to the necessity of a typological and spatially diversified approach to the interpretation of changes in the ecological status of streams and in the formulation of proposals for their improvement and sustainability.

KEY WORDS: Ecological status of streams – water quality – erosion – suspended sediments – hydromorphology – water pollution – stream modification – Water Framework Directive.

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1. Introduction

Changes in stream environments represent one of the most sensitive indicators of anthropogenic effects on the landscape and natural environment. Over long periods, the pressure of intensive land use produces changes in streams that involve a range of ecological aspects, from actual modifications in the river network, the hydromorphological condition of riverbeds, the conditions for sediment transport and erosion processes to changes in the surface water quality. These aspects of the change in the hydrological environment were historically studied as separate processes. However, their effect on the stream ecosystems is synergistic. Previous findings on the complex nature of individual aspects of water environment changes resulted in a shift in EU water management and legislation, whereby the traditional approach for water quality monitoring and assessment has been replaced by the new framing concept of the ecological status of streams, based on the complex approach (EC 2000).

A comprehensive approach to researching and managing the ecological status of surface waters is a fundamental principle of the key document regulating water management in the European Union, the Water Framework Directive of the European Community 2000/60/EC (WFD). The term “ecological status” is defined here as an expression of the quality and function of the hydrological ecosystem associated with surface water (EC 2000, Fuksa 2007). The ecological status of surface water is assessed on the basis of its biological, hydromorphological and chemical qualities. In the context of these three aspects, the individual components are regarded as parts of an integrated complex system. This new approach requires the creation of a new methodological tool for the classification, monitoring and evaluation of the ecological status of surface water at the experimental research level (Matoušková 2008b; Šípek, Matoušková, Dvořák 2009) and a legislative tool and methodology for water management (Fuksa, Kožený 2005; Langhammer 2007; Langhammer et al. 2009; Langhammer, Hartvich, Zbořil 2010).

Changes in the ecological status of surface water have strong spatial-temporal dynamic features. The temporal dynamics of changes in the individual aspects of the ecological status is basic to traditional research questions about the ecology of surface water, whether viewed in terms of surface water quality (EEA 2001; Johnes 1996; Panepinto, Genon 2010; Volaufová, Langhammer 2007), the hydromorphological status of streams (Friberg, Pedersen, Sandin 2008; Weiss, Matoušková, Matschullat 2008) or the potential for erosion and transport processes during flooding (Butt, Waqas, Mahmood 2010; Kliment, Kadlec, Langhammer 2008; Walling, Fang 2003). This article presents an original geographical approach to the analysis of the spatial-temporal changes of key aspects of the ecological status of streams: water quality, hydromorphology and fluvial processes. The presented methodologies were developed and applied to facilitate the analysis and interpretation of processes across spatial scales and geographical conditions with respect to the established EU environmental legislation and guidance documents. Selected model catchments are used to illustrate the changes in the ecological status of streams and applicability of analytic methods. Czechia provides suitable conditions for this type of analysis. Intensive anthropogenic stresses have affected virtually the entire river network, including headwater regions, during the 20th century because rapid and fundamental improvements in water quality have occurred since 1990, a result of political changes and the application of European environmental legislation measures.

2. State of the art in methodological tools for assessing the ecological status of stress

2.1. Analysis of the spatial aspects of changes in surface water quality

The spatial scale is one of the most significant drivers for selection and the application of assessment methods and is therefore a key factor limiting the scope and precision of assessment. At the microscale and mesoscale levels, scaled from experimental plots to individual catchments, the primary concern is to identify direct pollution sources and to spatially address the distribution of pollution from nonpoint pollution sources. At this level, nonpoint pollution sources play a decisive role in changes in water quality in streams (Langhammer, Kliment 2009; Volaufová, Langhammer 2007). A significant research problem is the ability to accurately quantify pollutant emissions from point sources. Due to the small volume of emissions produced, these sources are usually not recorded in the pollution source databases. Hydrodynamic models coupled with a water quality module (e.g., MIKE 11, SWAT, and MIKE SHE) play an important role in these circumstances. This approach facilitates the calculation of the pollution load balance and allows simulations of the spread of pollutants in streams and the effects of the changing structure of pollution sources (Kaiglová 2010, Langhammer 2004a).

At the macroscale level, i.e., the level of complex basins, structural differences in water quality are linked to the size of the stream and the location within the basin (Langhammer 2005). A mathematical model is the basic tool for the analysis of spatial aspects of changes in water quality over the longitudinal profile of the stream. This model facilitates the calculation of the pollutant load balance and dynamics, serves to localize the range of pollution sources and allows for the simulation of the effectiveness of pollution reduction measures. The complex models, e.g., MIKE Basin, enable the simulation of the simultaneous effects in space and time of direct and nonpoint pollution sources (Kaiglová 2010). Hydrodynamic models simulating changes in stream systems in the steady state (QUAL2E/K), or dynamic changes in the longitudinal profile (MIKE 11; Langhammer 2004b), are used for a detailed description of the dynamic distribution of loads and for simulating changes in water quality in the stream basin.

With regard to providing information on water quality changes in individual basins, there is a need for approaches that fill the gap between high levels of detail at specific points or catchments and the understanding of processes and trends occurring in large rivers or complex basins. To understand the synergistic effect of processes occurring in different parts of basins, it is necessary to apply modeling and geostatistical approaches, combining the required level of accuracy with spatial extent and reflecting the major driving forces of changes in the landscape. The need for such an approach, combining the required accuracy with a high spatial extent for the assessment of complex processes, has been solved in two aspects – linear and areal. For an analysis of the linear aspect, we tested generalized steady-state hydrodynamic models, designed for long stretches of complex rivers. The application of generalized, but precise, models over a large spatial extent allowed for the analysis of water quality changes in the continuum of the longitudinal profile of the whole stream and for the simulation of the effects of considered depollution measures or the impact of legislative regulations under different hydrological situations. Moreover, a new approach was proposed and tested for the areal aspect by Langhammer (2010) to enable the assessment of the spatiotemporal patterns of water quality changes at the macroscale, comprising complex basins. The method expresses the spatial distribution of long-term trends in water quality changes based on the results of long-term water quality monitoring.

The assessment is performed with a combination of regression and cluster analyses. First, the time period covered by water quality monitoring in the entire dataset is partitioned to produce intervals corresponding to the major typical periods of water quality development. For each period, the slopes of the trend lines are calculated for every parameter at each monitoring station. These slopes are then used as the source data for a cluster analysis. The aim of the cluster analysis is to detect the typical patterns defined by the changes in water quality and to identify the clusters of monitoring stations that show corresponding trends in water quality changes for the assessed parameters. This method for the analysis of spatial changes in water quality was used to analyze the spatial patterns of water quality changes in the Czech part of the Elbe River Basin (Langhammer 2010). The data from a total of 160 profiles from the water quality monitoring network for the period of 1970–2010 (CHMI 2010) were used for the analysis.

2.2. Monitoring and assessment of the hydromorphological condition of streams

The hydromorphological condition of streams is a comprehensive indicator that reflects the intensity of the overall anthropogenic impact on the river network and the ecological status of the streams. Modifications to the river network, stream channels and flood plains greatly affect flow dynamics and fluvial morphological changes in riverbeds. These effects substantially influence the oxygen regime. For this reason, they also affect the self-purification processes occurring in the stream. The hydromorphological conditions of the stream represent factors that act on both basic components of the ecological status – chemical and biological. This connection is also clear in the system definition of ecological status and its components in the context of the Water Framework Directive 2000/60/ES (EC 2000), its related methodological documents and standards (CEN 2002; EN 14614 2004) and national water management legislation.

Numerous hydromorphological methods have been developed; more than 20 methods are currently used in Europe (Orr et al. 2008; Balestrini, Cazzola, Buffagni 2004; Weiss, Matoušková, Matschullat 2008). Today, the primary emphases of hydromorphological research includes the quality of the physical habitat of water bodies, the identification of reaches that meet the requirements for good ecological status (in the case of artificial and heavily modified water bodies with good ecological potential) and the identification of heavily modified reaches so that appropriate measures for the improvement of their condition can be proposed (Matoušková, ed. 2008; Matoušková, Weiss, Matschullat 2010). Fernandéz, Barquín, Raven (2011) reviewed more than 50 methods used worldwide to characterize river habitats. Methods of characterizing river habitats differ mainly with respect to three features: (1) the objectives for which they were designed, (2) the time required for their application and (3) whether they measure or evaluate characteristics.

New methodological tools were designed and tested by the authors to monitor and evaluate the hydromorphological condition of streams in basins on various spatial scales and in the presence of different degrees of anthropogenic impact. Initially, based on field surveys, particular use was made of the EcoRivHab (Matoušková 2003, 2008a; Matoušková, ed. 2008) and the Hydroecological Monitoring Method (HEM; Langhammer 2007). Methods from other countries were also used in the research on basin modeling. The selection of a method depended on the size and characteristics of the studied basin.

A well-established method, Rapid Bioassessment Protocols For Use in Streams and Wadeable Rivers (RBPs; Barbour et al. 1999), which served as a national standard for research on the ecological status of North American streams, was tested at the macro- and meso-levels. Hydromorphological research was performed only on the basis of 10 evaluation parameters monitored in the field as part of a comprehensive hydrobiological survey (Matoušková, ed. 2008). To meet the requirements of a nationwide survey at the mesoscale, the German LAWA-Overview method (LAWA-OS) was applied. The subject of the evaluation is the functioning of the river ecosystem and not the diversity of its structures. Emphasis is placed on the use of existing maps and materials. The method assigns 17 individual parameters to represent principal ecological functions related to morphodynamics, habitat functions and flow fluctuations (Matoušková 2008a). The HEM Method (Langhammer 2007), applied as the standard for hydromorphological research in Czechia, is based on a set of 17 parameters. This method combines information from field surveys and remote data sources.

The LAWA-Field Survey method (LAWA-FS) is based on a detailed field survey in which segments of homogeneous lengths (50–500 m) are defined according to the width of the channel (LAWA 2000). For this reason, this method is especially appropriate for research at the microscale. The research is based on a group of 25 parameters. The classification system of both LAWA methods follows the minimum principle; it is not possible, for example, to compensate for poor riverbed dynamics by good floodplain dynamics, thus the worst condition in any class defines the overall quality (Kamp, Binder, Hoelzl 2004). The River Habitat Survey (RHS; Environment Agency 2002) method separately assesses the basic fluvial-morphological characteristics of the stream and the degree of anthropogenic transformation. The evaluation is not performed along the entire length of the segment. Ten defined sections of the same length (ca. 10 m) are chosen at an equal distance from one another (ca. 50 m) for use in the evaluation. This method offers a high level of detail due to the large number of characteristics used for monitoring. It is possible to include the EcoRivHab method in the group of detailed assessment approaches that were applied to smaller streams as well as meso-level basins. In all, 31 parameters are assessed in this method.

Comparative field studies have shown that the results achieved by the different methodologies are comparable (Weiss, Matoušková, Matschullat 2008). However, the extent of this comparability is limited due to the variety of assessment principles and procedures used in the monitored zones and the variety of individual parameters (Šípek, Matoušková, Dvořák 2010). Different approaches for evaluating the quality of physical habitats in streams were applied during our study in a number of basins that varied in physiography and human impact. These studies included streams in undisturbed environments (e.g., the Upper Blanice River, Křemelná River, and Klíčava River), streams in landscapes with a mixture of agricultural activities and types of settlements (e.g., Košínský Creek, Liběchovka River, Lišanský Creek, and Rakovnický Creek), streams with strong riverbed modifications (e.g., Rolava River, Litavka River, and Stropnice River) and basins with heavily modified hydrographic characteristics that are located in an industrial region (e.g., the Bílina River). Overall, more than 1,400 km of streams were mapped in Czechia. At least two different methods were applied in the majority of the studied basins.

2.3. Analysis of changes in erosion and transport processes in the basin

The assessment of erosion processes occupies a special position in the evaluation of the ecological status of streams. In addition to actual stream erosion, soil water erosion is a primary process, found to varying degrees, throughout the watershed. Erosion produces sediments that cause surface water turbidity during periods of high water levels, reduce the flow capacity of streams and enter the accumulation areas of reservoirs. Accelerated soil erosion alters the natural fluvial dynamics in basins and modifies the sediment balance and quality of streams. In areas of intense agriculture, the chemical content of erosion products may become a dominant source of pollution in surface waters and may thus affect water quality and aquatic life.

The development of measurement and monitoring devices, analytical treatment techniques and geoinformation technologies caused important shifts in the field of soil erosion and material transport research over the past decade. The presented research is aimed at the integration of various methods, e.g., field surveys, laboratory analyses, the monitoring of suspended sediments and selected parameters of surface water quality, GIS analysis and mathematical modeling. The combination of various methodological approaches is important for the analysis and interpretation of fluvial processes at different spatial and temporal scales, as well as for heterogeneous physiographic conditions.

As a basic method, the USLE (Universal Soil Loss Equation) in the RUSLE version (Renard et al. 1994), supplemented by multi-criteria point evaluation of principal erosion factors, was applied to estimate the erosion load. Based on experience from field surveys and modeling efforts, a new methodological approach was proposed to identify the zones showing an increased risk of soil erosion (Kliment, Langhammer 2005). The methodology is based on five key factors affecting soil erosion processes: the geomorphological bedrock values; the relief slope factor; the coefficient of soil erodibility (Janeček et al. 1992); the CORINE land cover database for 1992 and 2000 (MŽP 2010); and the precipitation coefficient, H_{20}/H (Kliment, Kadlec 2007). The methodology was tested in basins with varying physiography and land use in different regions of Czechia at the mesoscale level (e.g., the Blšanka, Loučka, Olšava, Blanice or upper Opava River basins) and at the microscale level (Čechtický Creek at Černičí). A semi-empirical modeling tool was tested in selected model basins to determine changes in the erosion potential.

The suitability of a variety of up-to-date modeling tools for use in the conditions found in Czechia was tested in the model catchments. The WaTEM/SEDEM (Van Oost, Govers, Desmet 2000; Van Rompaey et al. 2001) and USPED models and the semi-distributed American models, AnnAGNPS and SWAT (Arnold et al, 1998; Bingner, Theurer, Yuan 2003), were applied to the Černičí experimental catchment (Vysloužilová 2010). Moreover, both semi-distributed models were used to model the Blšanka River Basin (Kliment, Kadlec, Langhammer 2008). Changes in land use, including changes in crop rotation and crop variety, were included in the models.

3. Major changes in the ecological status of streams

3.1. Spatial differentiation in trends of water quality changes

During the past two decades, a basic transformation affecting key issues of pollution and surface water quality has occurred in Czechia. During the late 1980s, the emissions of pollution from industrial and municipal sources insufficiently equipped with wastewater treatment systems reached a maximum. These sources produced heavy pollution within vast segments of the stream network. The majority of the network's components reached minimum levels of water quality. Under these circumstances, the primary aspects of this research focused mostly on the identification of critical sources of impurities, on the search for effective tools to assess changes in pollution loads and on models for simulating the effectiveness of various measures (Langhammer 2004b).

Scenario-based simulations enabled the identification of the impacts of large sources of emissions, evaluation of their influence on water pollution at different flow levels and testing different scenarios for pollution reduction measures. The longitudinal profile of the Elbe River in the segment at Pardubice, a key section for the development of pollution in the Czech part of the Elbe River, was analyzed using a steady-state water quality model (i.e., QUAL2E). Simulations of water quality changes in the longitudinal profile associated with contamination levels at historic time horizons representing key periods of changes in stress in the Elbe (i.e., 1990–1991, 1993–1995, 1998–1999 and 2004–2005) were analyzed with theoretical scenarios corresponding to the application of legislated emission limits during the previous two decades. These legislated limits were specified in government decrees 171/1992 Sb., 82/1999 Sb., 61/2003 Sb. and 229/2007 Sb. (Fig. 1).

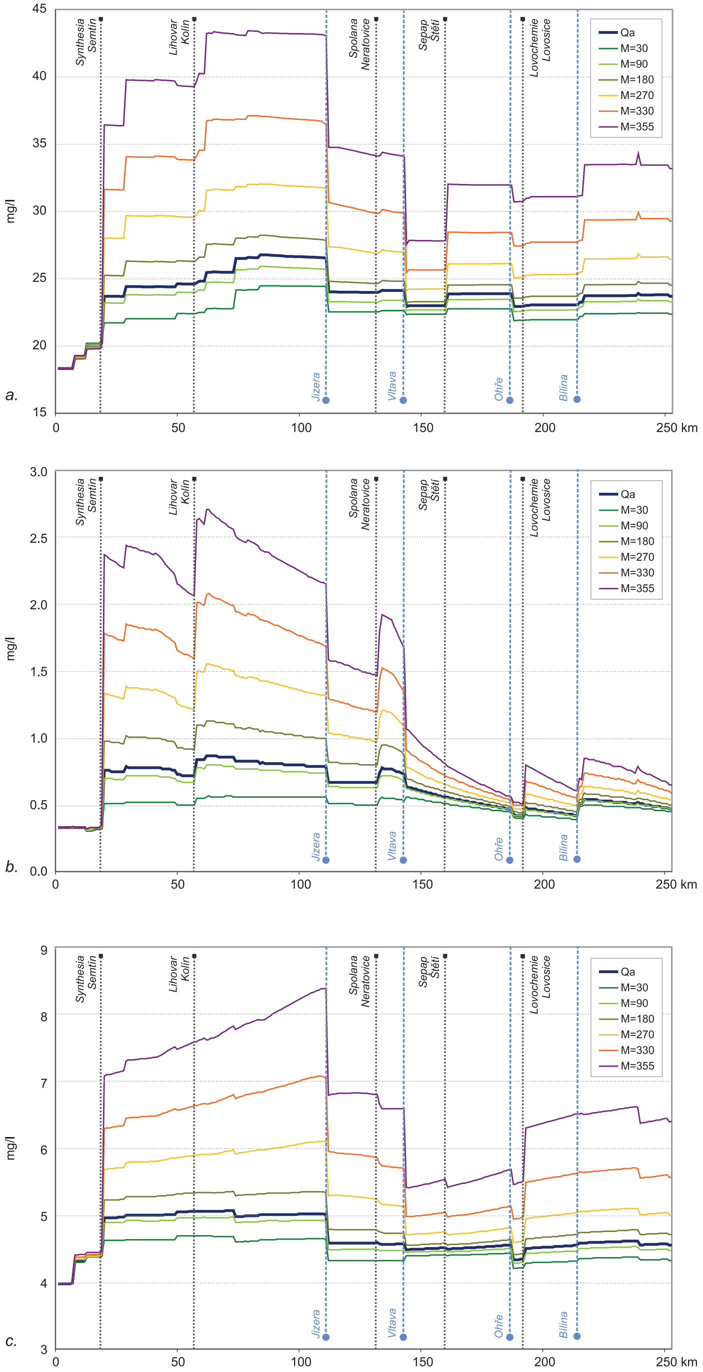

Fig. 1 – Results of QUAL2E model simulation of impact of application of national emission limits (171/1992 Sb.) on water quality changes in Elbe river longitudinal profile under variable runoff conditions. Simulated indicators COD_{Cr} (a), N-NH_4 (b), N-NO_3 (c). Data: CHMI, WRI.

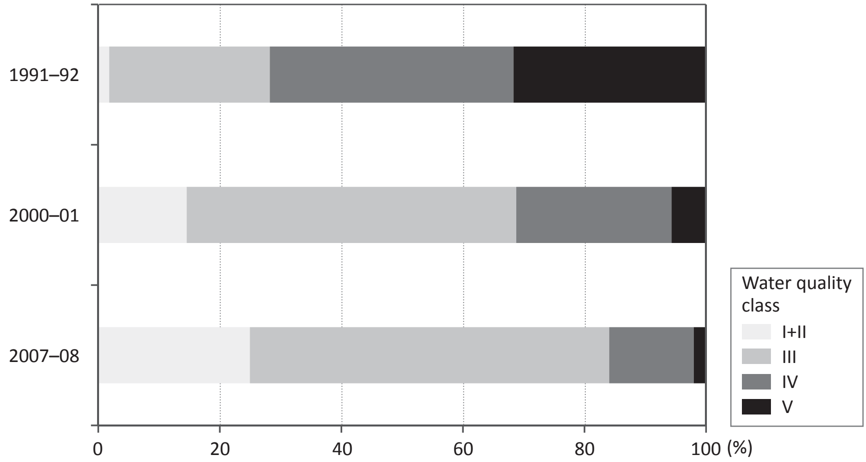

Fig. 2 – Change of length of stream segments, classified according surface water quality standard CSN 757221 in period 1991–2008. Data: WRI.

The results of a simulation performed using the QUAL2E model at discharge levels of $Q_{30,\ 90,\ 180,\ 270,\ 330,\ 355}$ and at long-term average flows was focused on the key balance water pollution indicators (BOD5, COD_{Cr}, N-NH_4^+, N-NO_3^- and P_{total}). The performed simulations (Fig. 1) proved the effectiveness of the proposed and applied measures. This simulation analysis, which used the Elbe as an example, showed the importance of gradual changes in legislation regulating direct pollution emissions. The pollution concentrations in the simulations, based on the levels of regulation in effect from the beginning of the 1990s, are greater than the current level of pollution in the stream for the majority of the indicators considered. However, the simulation also shows that the scope for reducing pollutant concentrations in streams through further reductions of emissions from large sources of pollution became nearly exhausted. The concentration of remedial measures on the lower reaches of large rivers and the absence of systematic measures in the smaller streams in the basins headwaters produces considerable spatial differences in the development of water quality within the fluvial network. Moreover, this pattern of management changes the trends affecting the polarization of stream loads based on the size of the streams.

A newly designed methodology for the analysis of the spatial polarization of trends describing changes in water quality enables the assessment of the spatial dynamics of water quality development and the identification of critical areas within basins (Langhammer 2010). The analysis, performed on the Czech segment of the Elbe River basin with data from 160 profiles from the quality network in the period 1970–2009, confirmed the growing differences in the spatial changes of water quality and identified areas in which water quality development was critical. The results show that water quality has not continued to improve in a major part of the stream network in the basin (Fig. 3). Positive changes are restricted almost exclusively to the main river basin and to the area in which the surface water quality is directly influenced by large sources of direct pollution. The areas showing positive change include

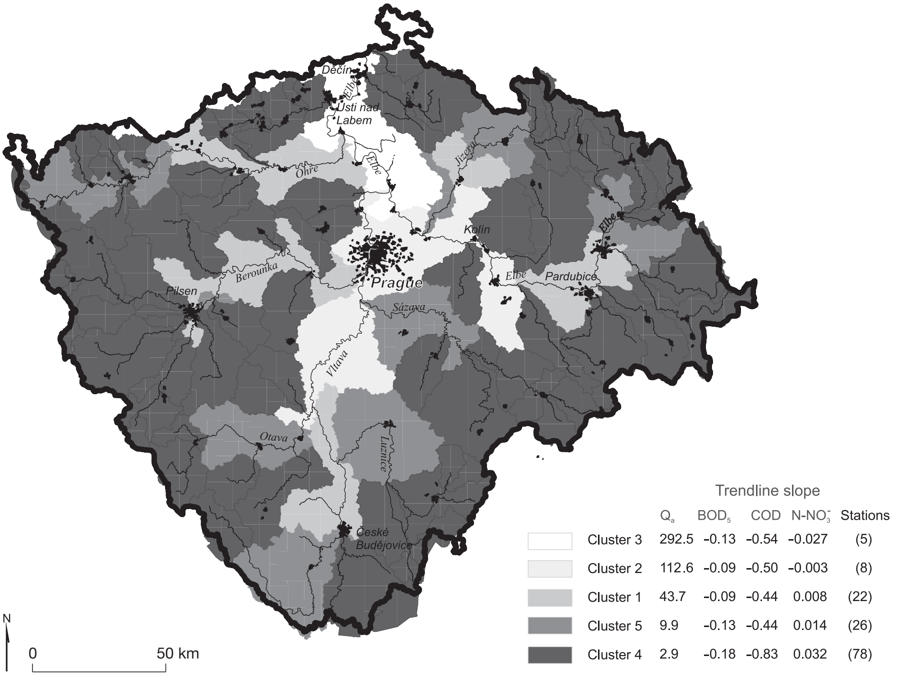

Fig. 3 – Spatial differentiation of water quality change trends in Elbe river basin in period 1970–2009. Data: CHMI.

the middle and lower segments of the Vltava, Elbe, Ohře, Berounka and Jizera Rivers. In contrast, extensive parts of the basin show long-term increases in nutrient loading and organic pollution. The results of these analyses confirm that to achieve further changes in water quality in the lower streams, it is essential to improve the condition of small streams in rural areas.

3.2. Changes in the hydromorphological conditions of streams

The present man-made modifications affecting streams in Czechia generally date from the beginning of the 19th century, when the development of shipping and industrialization required that the larger streams be navigable. Overall, the greatest modifications to the hydrographic network occurred during the 20th century. To date, approximately 28% of the streams in Czechia have been modified (Just 2003). The greatest extent of modification (almost 40%) has occurred on smaller streams flowing through rural areas (Matoušková 2003). Riverbeds and riparian zones have been modified for various purposes, including amelioration measures, the regulation of water flow, the stabilization of slopes and channel course conditions, the limitation of stream erosion, active anti-flooding measures, the use of the water supply, and the construction of power stations and reservoirs.

Research performed on a set of model basins focused on detailed analysis of changes in the condition and habitat quality of streams in different environments demonstrated that most streams in Czechia are classified as being moderately to heavily modified. The examples discussed below demonstrate that the changes in the condition and habitat quality of the streams in a given basin are determined by the degree of socioeconomic activity and the basin physiography.

The headwaters in protected areas and national parks occupy an exceptional position. In the surveyed Upper Blanice, Klíčava and Liběchovka basins, for example, almost 80% of the reaches occupy the 1st or 2nd ecohydromorphological class (EC). Their exceptional status is due to their geographical locations and to very low anthropogenic activity within these basins during the past 50 years. Areas with intensive agricultural pressure and related amelioration measures that negatively influence the characteristics of stream habitats primarily occupy the 3rd or 4th EC. Many water bodies in rural areas show good potential for improvement of their ecological status if restoration measures are applied because of sufficient free space in the floodplain and a low to moderate level of surface water pollution. The habitats of streams in urban and industrial areas are heavily transformed; these streams occupy the 4rd or 5th EC using the EcoRivHab and HEM method.

The Klíčava River is an example of a basin whose hydromorphological conditions are generally very good. Conservation measures, e.g., the Křivoklátsko protected area, the Lánská preserve and the water supply protection zone of the Klíčava reservoir, exert a positive influence on the status of the stream. This basin was evaluated with the EcoRivHab method (Matoušková 2003) and RHS (Environment Agency 2002) on the basis of a field survey. A total of 40% of the Klíčava basin is placed in the 1st EC. This designation represents a natural or near-natural condition. A total of 48% of the basin is placed in the 2nd EC. The reaches in Lánská preserve were considered to have a particularly high hydromorphological value and were used to define the reference condition. Only 12% of the whole watershed is anthropogenically modified, corresponding to the 3rd and 4th EC. The reaches in the headwaters of the river could be returned to a near-natural state without any major complications. In contrast, the lower course of the Klíčava River, i.e., below the water supply reservoir (4th EC), cannot be restored to a good ecological status because the modified stream bed and transformed riparian zone must fulfill their current purpose (Matoušková, ed. 2008).

The largest number of hydromorphological assessment methods was applied in the Rolava basin, which represents a typical basin with a mixture of activities. The EcoRivHab (Matoušková 2003), LAWA-FS (Kern et al. 2002) and HEM (Langhammer 2007) methods were used here. The hydromorphological state of these streams can be described as moderately anthropogenically modified, with significant variation among the various streams. The degree of anthropogenic modification increases from the upper to the lower courses. In the upper part of the basin, with the exception of the reaches in the vicinity of Nejdek, the river has a near-natural character (40% in 1st and 2nd EC). In the middle course, the reaches showing a high ecological status and thus significant modification overlap urban reaches. The lower courses of the Rolava River and Nejdek Creek (Fig. 4) are significantly modified, 12% of the length of the streams is

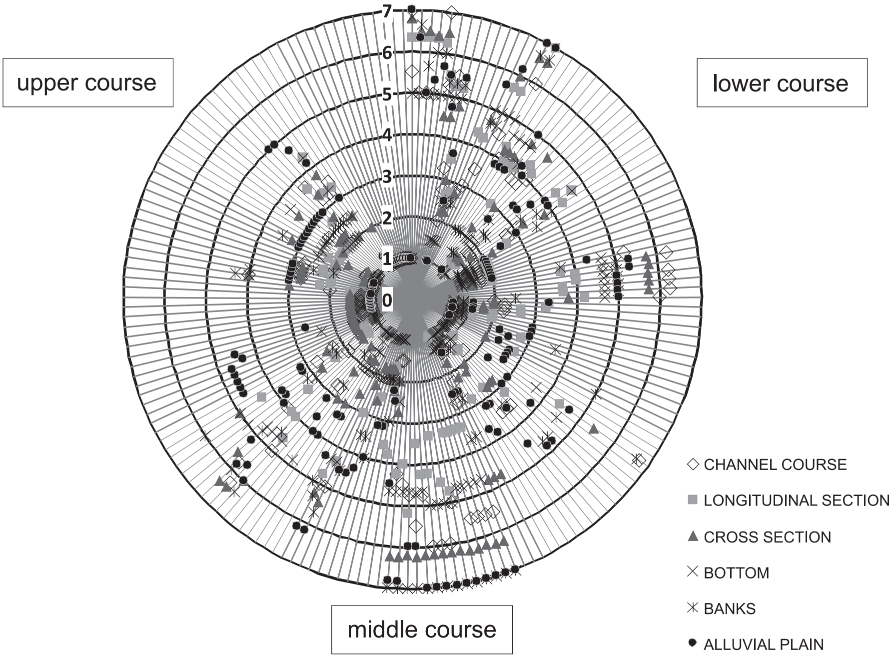

Fig. 4 – Ecohydromorphological condition of individual zones in the Rolava River assessed with the German LAWA-FS method. Seven ecomorphological degrees (1 – ES best condition, 7 – ES worst condition). Data: Charles University in Prague.

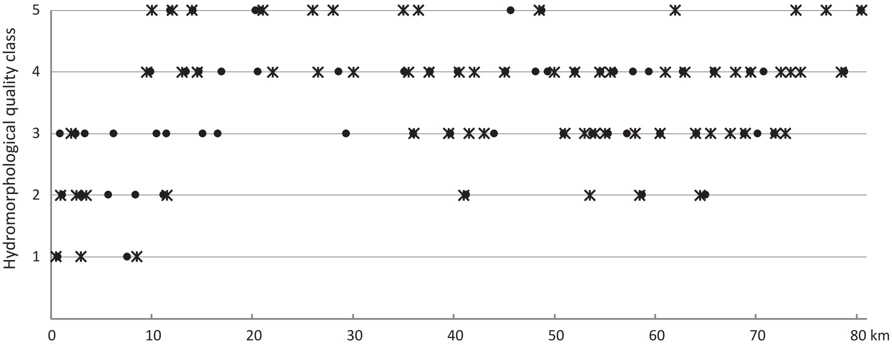

Fig. 5 – Ecohydromorphological condition of the Bilina River, assessed with the aid of EcoRivHab and LAWA-OS. Five ecomorphological degrees (1 – high status, 2 – good status, 3 – moderate status, 4 – poor status, 5 – completely changed status). Data: Charles University in Prague.

designated as 4th and 5th EC (Matoušková, ed. 2008; Beranová 2011) in the case of EcoRivHab and HEM methods.

The Bilina River represents an example of a basin that shows extreme anthropogenic modification by surface mining and industrial activity with heavy impacts on the hydromorphological state of the river network. The assessment of this basin was conducted with three different methods: EcoRivHab (Matoušková 2003), HEM (Langhammer 2007), and LAWA-OS (Kern et al. 2002). Natural and near-natural segments represented 15% of the length of the Bilina (Matoušková, Dvořák 2011). Almost 30% of the length of the river contained segments that were moderately anthropogenically modified. More than 50% (in the case of LAWA-OS, more than 60%) contained heavily and very heavily modified segments (Fig. 5). The general hydromorphological condition of the stream is therefore very disturbing. However, two revitalization projects have been proposed to mitigate the extreme anthropogenic pressure on the streams. These projects include the revitalization of the Ervěnice corridor and the revitalization of the segment of the Bilina between Most and Chemopetrol (Matoušková, Dvořák, Kyselka 2010).

The implementation of improvements to the hydromorphological condition of streams is often difficult because of natural conflicts of interest in the floodplain. The most frequent pressures result from socio-economic development, including the construction of industrial and commercial zones, urbanization and suburbanization. The need for efficient flood protection measures is a consequence of socioeconomic development that places pressure on the hydromorphological condition of streams. The studies reviewed in this paper showed that appropriate measures could be used to achieve significant improvements even in substantially modified basins. For example, biotechnical modifications can be applied to the stream bed. The results achieved in the model basins indicate that insufficient improvements in the hydromorphological state of streams impose substantial limits on the achievement of further improvements in the surface water quality of the streams.

3.3. Changes in the erosion potential and transport of suspended solids in basins

According to current estimates, up to 40% of arable land in Czechia is affected by manifestations of water erosion (Dostál et al. 2006). The latest significant acceleration of erosion processes in the countryside is connected with the conversion to collectivized large-scale production from the 1950s through the 1970s. Accelerated erosion is demonstrated by the activation of the historic drainage systems (Kliment, ed. 1997) and the development of colluvial material (Zádorová et al. 2011). In connection with diminished agricultural production in the second half of the 1990s, formerly cultivated fields became grasslands or, in some cases, forests.

Research in experimental basins confirms that accelerated erosion is a threat, particularly in foothill and highland areas. In the studied areas, the greatest changes occurred in the mountainous and mid-level areas of the basins. The Blanice River basin might represent an example of this process (Kliment, Kadlec 2007). The application of the RUSLE empirical model in conjunction with the calculation of the reduced average annual loss of soil due to erosion between 1992 and 2000 shows that the reduction in the area of arable soil is balanced by a compensatory conversion to grassland and forest and shows a significant

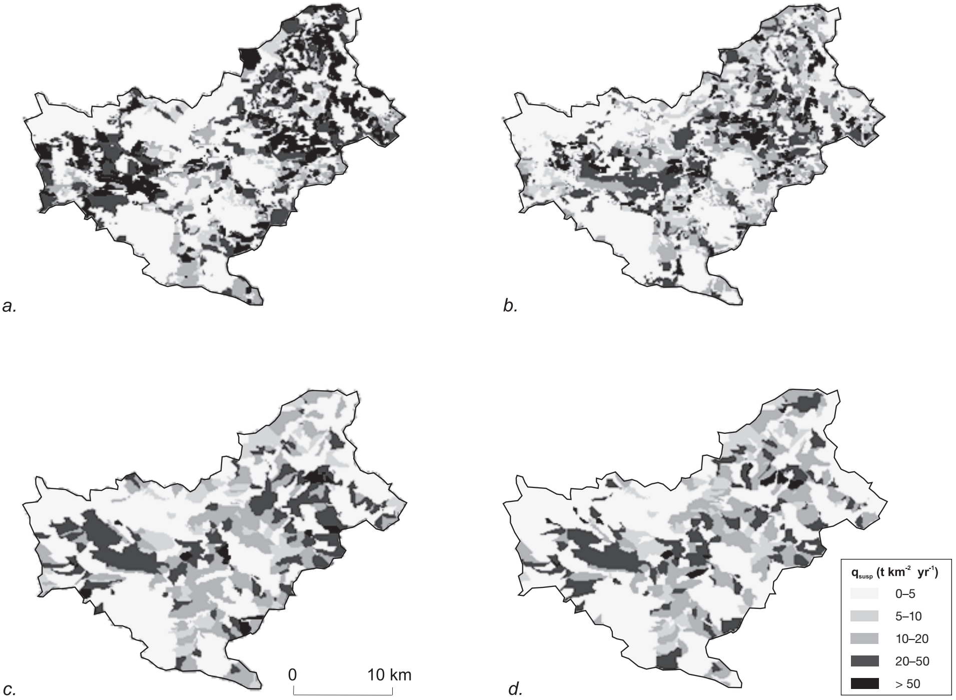

Fig. 6 – Changes in the specific discharge of suspended sediments in the Blšanka River basin as shown by SWAT and AnnAGNPS models; a – SWAT 1995–99, b – SWAT 2000–04, c – AnnAGNPS 1995–99, d – AnnAGNPS 2000–04.

reduction in the overall degree of erosion potential. Analogous results directly confirm the modeling analysis performed in the Olšava and Upper Opava River basins (Jablonská 2008; Kliment, Kadlec, Langhammer 2008).

Changes in erosion and transport processes also greatly influence changes in the structure of cultivated agricultural fields. A potential example is the Blšanka River basin (Kliment, Kadlec, Langhammer 2008). Here, changes in crop rotation were included in transport models addressing erosion processes and suspended solids. The conversion of cultivated land to grassland by the reduction in the areas of hops and other plants (particularly wheat) is reflected in a reduction of average annual erosion losses in the entire Blšanka basin from 1.16 t.ha^{-1}.year^{-1} in 1995 to 0.93 t.ha^{-1}.year^{-1} in 2004 (according to the RUSLE method). According to the AnnAGNPS and SWAT models, estimates of the annual decrease in the volume of transported sediments caused by land-use changes range from 10–30% (Fig. 6).

Erosion processes and sediment transport are highly sensitive to the type of crop cultivated, as shown by studies using the WaTEM/ SEDEM model in the little-surveyed area of the Čechtického p. – Černičí catchment (Vysloužilová 2010). The modeling results and the trend toward reduced volumes of transported suspended sediments were also confirmed by a time series analysis that included scale considerations. It was found that the amount of transported

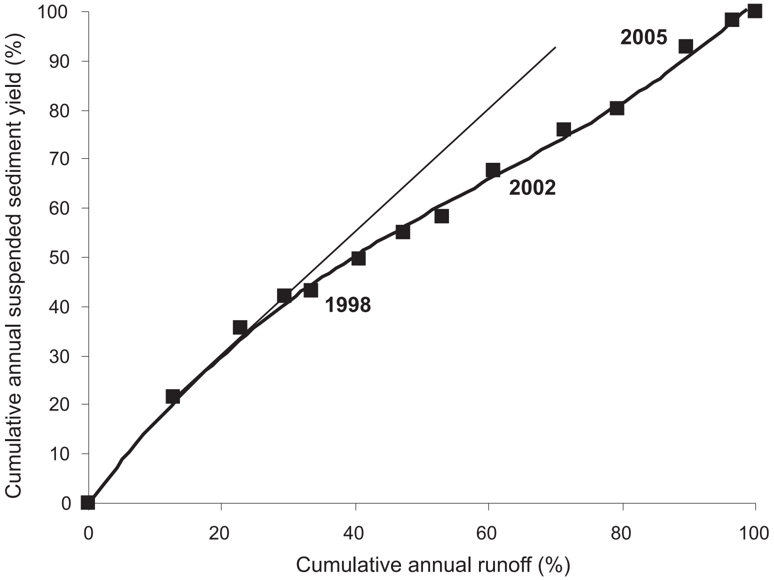

Fig. 7 – Development of suspended sediment transport in relation to water flow in the Holedeč profile, Blšanka River (1994–2007). Data: Charles University in Prague.

suspended solids decreased, relative to water flow, beginning in the late 1990s in the modeled Blšanka, Loučka and Olšava River basins. This decrease was followed by reduced values of the maximum and average suspended sediment concentrations (Kliment, Kadlec, Langhammer 2008; Langhammer, Kliment 2009; Fig. 7).

Changes in suspended sediment transport can be linked to current erosion conditions and changes in climate evolution. Jablonská's (2008) analysis of the Olšava basin demonstrated that during the recent warm winters, a higher proportion of suspended solids were transported year-round. In conjunction with reduced water flow and dry conditions, the proportion of suspended sediments is reduced during the growing season. During the previous decade, exceptionally intense erosion and a high volume of sediment, especially at local levels, were observed as a consequence of extreme flooding. Moreover, one of the most common assumptions included in future climate change scenarios in Czechia is that extreme rainfall-runoff events will increase (Kalvová et al. 2002). For this reason, effective erosion control measures are one of the priorities for water management and regional administration.

4. Discussion

The research of the ecological state of streams demonstrated that geographical aspects and approaches are vital for identifying appropriate methods of analysis for the current state, defining context for interpretation of changes and designing appropriate restoration measures. The selection of appropriate methods should reflect the heterogeneity of physiographic conditions, anthropogenic pressures, spatial scale of assessment, spatial distribution of the driving forces of processes affecting the ecological state and connectivity of individual elements of the fluvial system.

The spatial scale at which an evaluation is conducted is a fundamental factor in surface water hydrology. The spatial scale at which investigations are conducted in the life and earth sciences represents the basic explanatory framework defining the characteristics of the processes occurring at a given spatial level, thus determining the methods to be used for the identification, analysis and interpretation of these processes.

The fundamental spatial attribute associated with the identification of the ecological status of streams is the stream order. This attribute is traditionally seen as the primary factor reflecting the environmental conditions of the stream and explaining the characteristics of the processes that occur within the stream (Goudie 1993, Rosgen 1994, Strahler 1957). Empirical observations demonstrate a direct linkage between the stream order and the resulting characteristics of the processes affecting the ecological status of the given environment, expressed, e.g., by the surface water quality (Langhammer et al. 2011; Verdonschot, Nijboer 2004; Wasson et al. 1996). The stream order is reflected in the physiographic conditions and indirectly in the socio-economic conditions of the given environment. Through this linkage, the stream order predetermines the spatial distribution of activities in the landscape and the resulting ecological status of the stream.

Moreover, the spatial scale represents the criterion that directly determines the level of detail, accuracy, and characteristics of the input data and the research methods needed for the acquisition of the data. The spatial scale expresses the chosen degree of generalization and the schematization of the processes and analytical techniques. In this way, it significantly influences the accuracy and characteristics of the output (Messner, Meyer 2006). The analysis of individual processes is always linked to the functional generalizations of their description. These generalizations are closely tied to the spatial generalization of the data and to the methods used for the analysis of the processes (Tab. 1).

The effect of spatial scale can be shown by the analyses of spatiotemporal changes in surface water quality in Czechia where a rising polarization in trends of water quality in large and small streams affects the research methods, ranging from the level of individual monitoring sites, modeling of pollution spread in streams to the geostatistic assessment of changes in complex basins. The combination of a generalized hydrodynamic water quality model and geostatistic spatiotemporal analysis allows for the identification of the effect of key processes driving the water quality changes in recent decades. These are changes in agriculture and large industrial and municipal direct pollution.

The major reduction in emissions from key industrial facilities at large rivers occurred during the first half of the nineties followed by the reduction of the emissions from principal municipal sources in the second half of the decade. The massive investments in wastewater treatment facilities radically reduced the concentrations of most monitored pollutants in the principal streams. The exceptional extent and speed of these changes in water quality in the late eighties and early nineties and in the current state of water quality clearly

Table 1 – Influence of spatial scale on the selection of assessment methods and model type for assessment of water quality, hydromorphology and sediment transport

Scale	Area	Basin	Purpose of use	Character and precision of input data	Water quality assessment method	Hydromorphological survey methods	Assessment method for erosion and transport possesses
Macro	10^4–10^6 km^2	Complex fluvial system, regionally significant watershed system	Identification of critical area stresses, water protection management, modeling of legislative measure impact, change trend classification	Generalized spatial information, Limited extent of assessment parameters, Assessment in large time steps	Modeling distribution of potential flood stress, statistical models, simplified basin models (BASINS)	Evaluation and classification of stream system typology and framework for reference condition	Simplified methods for estimation of erosion risk, substance transfer and calculation of balance values, point methods
Meso	10^2–10^4 km^2	Fluvial network, significant stream basin, flooding of minor and medium extent	Modeled analysis of the impact of change in pollution stresses and basin land use change scenarios	Scale, time step and precision highly variable according to the purpose of the assessment	Basin models, water quality, GIS models, models based on complex empirical models (QUAL2E, NPSM)	Standard hydromorphological survey (HEM, LAVA OS, RBP, RHS, EcoRivHab)	Empirical and semi-empirical models based on USLE and its modifications (RUSLE, WaTEM/SEDEM, AGNPS, SWAT etc.)
Micro	1–10^2 km^2	Stream basin segments, micro basins	Flood prevention measures for buildings and property, damage calculation	High spatial precision data, high frequency of sampling, high level of measurement accuracy	Dynamic basin models (MIKE 11, MIKE 21 etc.)	Experimental methods of hydromorphological condition assessment based on physiographic and environmental characteristics (LAWA FS, RHS, EcoRivHab etc.)	Physically based models, dynamic continual simulations EROSION 3D, SMODERP

demonstrate the changes occurring in the sections of the river in Czechia. These sections are ranked according to individual classes of water quality (Fig. 2). On the contrary, the changes in emissions from nonpoint sources are stagnating despite substantial structural changes in Czech agriculture since 1990, especially the diminishing extent of arable land. The decline in overall agricultural production has not resulted in a reduction of pollution in small streams in rural basins. The small streams are suffering, as indicated by the poor long-term management of municipal waste treatment in small settlements, for example. At the same time, there are newly emerging problems stemming from changes to the agricultural subsidy policy and favoring the crops applicable for promotion of renewable resources, for example. The resulting sharp rise of shares of canola and maize, replacing traditional crops, has a negative effect on soil erosion vulnerability, associated material transport and nonpoint pollution.

The spatially polarized changes in water quality can be regarded as a primary cause of stagnating water quality at the level of small streams and represents a principal factor limiting the further development of surface water quality in the entire river network in Czechia.

Connectivity of fluvial systems is an essential aspect for understanding the complex nature of changes in the ecological state of streams in different basin zones. The headwater reaches of streams in rural landscape areas are exceptionally important in this context. Intensive farming represents the main source of pressure on aquatic environments. Intensive farming is associated with the acceleration of erosion processes and of material and nutrient transport to the streams. Moreover, intensive farming is often associated with the intensive modification of streams. Due to naturally low discharges in the headwater streams and reduced diversity of the hydromorphological characteristics in the modified channels, the function of self-purification mechanisms in these streams is severely limited. These limitations affect the ecological status of the stream because they have downstream effects. Furthermore, these limitations restrict the reaction of streams to the stresses and pollution emissions occurring in the downstream reaches.

The research performed in the model basins shows that the fundamental problem affecting stream pollution in agricultural areas is the concurrence of a high intensity of agricultural land use and a spatial concentration of local direct pollution sources without a corresponding level of wastewater treatment (Judová, Janský 2005; Pivokonský, Benešová, Janský 2001). Comparative studies in the rural basins of Blšanka, Loučka and Olšava (Langhammer, Kliment 2009) demonstrated the key effect of the location and spatial concentration of point pollution sources on water quality and the primary effect of these factors on the potential for the development of self-purification processes in stream basins.

The location of pollution sources in headwater areas is typical of highland streams and results from features of the topography. For the Loučka basin, the research discussed above confirmed that the location of local pollution sources in the headwaters prevents the evolution of self-purification processes in the stream despite the generally low volumes of pollutant emissions. The instream processes cannot eliminate the subsequent pollution produced by diffuse sources and as a result, the changes in water quality are very limited (Langhammer, Kliment 2009).

Kliment (2005) demonstrated a relationship between the average suspended sediment concentration and the potential for soil erosion in a watershed. The areas with the greatest changes in erosion potential are primarily located in the foothills and the highlands. In these areas, a notable reduction in the amount of arable land was balanced by a compensatory increase in the space occupied by pastures, permanent grasslands and forests. Positive developments resulted from changes in crop rotations and from the cultivation of crops that are less susceptible to erosion (Kliment, Kadlec, Langhammer 2008). These changes are also apparent in the reduced volume of transported suspended sediments.

The assessment of the hydromorphological conditions of streams in a variety of model basins assessed in different physiographic conditions demonstrated the linkages between the streams' high environmental burdens and the intensive modification of their hydromorphological conditions (Šípek, Matoušková, Dvořák 2009; Weiss, Matoušková, Matschullat 2008). In general, the degree of modification of the stream network increases from mountainous and foothill areas toward the mid- and low-level streams. As a result, the quality of the physical habitat of the stream decreases along this gradient. As a general rule, the headwater segments and smaller streams in protected areas show the highest level of ecological quality of the physical habitat. This pattern is effectively demonstrated by research performed in the Blanice basin. The greatest degree of modification in the stream network was recorded on the lower reaches of the Blanice River (exceeding 40%). The modifications of the network were performed primarily for flood prevention, agricultural drainage and improvement of agricultural production in the region. This alteration of the network has a significant impact on the characteristics of the runoff regime and on the surface water quality (Langhammer 2010).

To obtain accurate interpretations of the observed status and to search for solutions that facilitate the sustainable management of the aquatic environment, it is necessary to recognize and understand the complex linkages between (1) the ecological status of streams defined in relation to the natural environment and (2) the anthropogenic modifications that affect the ecological status of the streams. In terms of the Water Framework Directive (EC 2000), the basic tool for defining the typological link between the condition of an aquatic environment and naturally variable environmental conditions is the typology of water bodies (EC 2003). On the basis of the Water Framework Directive guidelines, the typology defines stream types with respect to the physiographic features, specific for the environment of individual EU countries (Fuksa, Kožený, eds. 2005; Langhammer et al. 2009). The typological categories reflect similarities in the conditions for the development of streams, dynamics of fluvial processes and the background levels of chemical, biological and hydromorphological parameters expressed as reference conditions (Bald et al. 2005; Nijboer et al. 2004).

Quantitative analyses of long-term changes in the parameters of the ecological status of streams according to the system of typology in use in Czechia (Langhammer et al. 2011) unequivocally confirm these basic functional differences. The typologically specific approach for the assessment of the ecological status of streams provides a basis for understanding the variability of the ecological status of streams and for determining effective solutions that foster the improvement of stream conditions.

5. Conclusions

Research focused on key aspects of the ecological status of streams has shown that anthropogenic interference with stream ecosystems in Czechia is complex. Exceptionally intensive changes in the ecological status of streams may influence individual stream features or have comprehensive effects. In either case, changes of this nature are observed only in heavily populated regions with industrial and related activities where ecological monitoring and rectification measures have traditionally been focused, as well as in smaller streams in agricultural regions.

The individual components of the ecological status of streams are clearly interdependent. This interdependence reflects not only the pollution of streams and sediments but also interference with the characteristics of the stream network, interference with stream hydromorphology, and disturbances associated with erosion and sediment transport conditions. These individual components of the ecological status undergo changes that have different intensities, dynamics, and temporal and spatial dimensions and require various approaches and tools for their objective analysis.

The rapid progress in measurement and sampling techniques and geoinformation technologies during the past decade has created an improved understanding of the interrelationships among the individual factors representing the human impacts on the landscape. These interrelationships also link the varied aspects of the ecological status of streams with the factors associated with the human impacts. The changes in ecological status of streams are determined by the intensity of anthropogenic pressure and spatial distribution of driving aspects, connectivity of the systems and physiographic properties of the landscape. The methodologies developed by the authors have helped to elucidate the spatial patterns of changes in water quality, hydromorphology and soil erosion and the relationship of these patterns with the physiography of basins, land-use changes and the distribution of socioeconomic activities.

The results of analyses conducted on a variety of model basins show that various processes are present in different environments and reflect the overall degree of anthropogenic pressure and the natural variability of environmental conditions. The findings from this research, conducted in model areas of different spatial scales and in varying geographical conditions, pointed to the necessity of a typological and spatially diversified approach to the interpretation of changes in the ecological status of streams and in the formulation of proposals for their improvement and sustainability.

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Shrnutí

HODNOCENÍ PROSTOROVÝCH A ČASOVÝCH ZMĚN EKOLOGICKÉHO STAVU TOKŮ V ČESKU: GEOGRAFICKÝ PŘÍSTUP

Příspěvek analyzuje geografické přístupy k výzkumu změn klíčových aspektů ekologického stavu toků Česka a jejich ovlivňujících činitelů a představuje původní metodické přístupy k jejich výzkumu. Výzkum je zaměřen na změny dynamiky tří vzájemně provázaných klíčových aspektů ekologického stavu toků Česka, které v uplynulých desetiletích prošly zásadním vývojem – změny jakosti povrchových vod, změny hydromorfologického stavu toků a změny dynamiky erozního ohrožení a látkového transportu toků.

Poznatky o ekologickém stavu toků, definovaném dle Rámcové směrnice o vodní politice ES jako komplex chemického, biologického a hydromorfologického stavu povrchových vod, jsou přes intenzivní monitoring jeho jednotlivých složek, stále omezené. Zásadní roli pro možnost poznání a interpretace změn ekologického stavu toku hrají geografické aspekty – prostorové měřítko, které určuje přístup k hodnocení, míru generalizace, dostupnost datových zdrojů, ale i metody hodnocení, výběr analytických nebo modelovacích nástrojů, dále prostorové uspořádání a koncentrace klíčových faktorů, ovlivňujících dynamiku procesů a v neposlední řadě kontinuita a konektivita systému.

Výsledky hodnocení, založené na analýzách ekologického stavu toků Česka v modelových oblastech s odlišnými fyzickogeografickými charakteristikami a rozdílnou úrovní antropogenní zátěže ukazují, že změny ekologického stavu jsou komplexní a vzájemně provázané na jednotlivých prostorových úrovních. K intenzivním a dlouhodobým změnám toků a jejich zátěže dochází jak v regionech se silnou koncentrací osídlení a průmyslových aktivit, tak v prostředí drobných toků v zemědělské krajině.

Pozorované výrazné zpomalení zlepšení jakosti vody a ekologického stavu toků, ke kterému dochází navzdory výrazným investicím do této oblasti, je vyvoláno dlouhodobou nerovnováhou ve směřování ochranných opatření na toky různých velikostních kategorií a nerespektováním synergií v působení jednotlivých zásahů do prostředí toků na jejich jednotlivých prostorových úrovních. Zásahy do prostředí pramenných oblastí a drobných vodních toků zásadním způsobem ovlivňují intenzitu přirozených procesů, podmínky pro rozklad látek, přenos zátěže mezi jednotlivými zónami toku a pro život společenstev. Bez omezení látkového transportu v ploše povodí a zlepšení hydromorfologického stavu toků se tak zásadně omezuje účinnost nákladných technických opatření ke snížení emisí a nedochází k pozitivní odezvě na tato opatření.

Analýzy, prováděné na případových studiích dále ukázaly, že změny ekologického stavu toků jsou determinovány nejen celkovou intenzitou antropogenního tlaku, ale že zásadní význam pro výsledný ekologický stav toku má prostorová distribuce zátěže ve vazbě na typově specifické charakteristiky přírodního prostředí a jeho modifikace. Zjištění tak ukazují nezbytnost dalšího vývoje metodických postupů a nástrojů pro hodnocení ekologického stavu toků. Přístupy, založené na analytické interpretaci jednotlivých složek nepostihují dostatečně komplexní charakter procesů, probíhajících v tocích a probíhajících změn. Klíčový je typologicky a prostorově diverzifikovaný přístup k hodnocení a interpretaci změn ekologického stavu toků, který umožní správnou intepretaci procesů změn ekologického stavu toků i formulace návrhů opatření k jeho zlepšení a udržitelnosti.

Obr. 1 – Výsledky výpočtu modelu QUAL2E, simulujícího dopad aplikace emisních limitů, daných nařízením vlády 171/1992 Sb. na změny kvality vody v podélném profile Labe za rozdílných hydologických podmínek. Simulované parametry: $CHSK_{Cr}$ (a), $N\text{-}NH_4$ (b), $N\text{-}NO_3$ (c). Data: CHMI, WRI.

Obr. 2 – Změna délky úseků toků, klasifikovaných dle jakosti povrchových vod dle ČSN 757221 v období 1991–2008. V legend: třída kvality vody. Data: HEIS, VÚV 2010.

Obr. 3 – Prostorová difefenciace změn trendů kvality povrchových vod v povodí Labe v období 1970–2009. Data: CHMI.

Obr. 4 – Ekohydromorfologický stav toku Rolavy hodnocený dle německé metodiky LAWA-FS do sedmi ekomorfologických stupňů (1 – nejlepší, 7 – nejhorší). Data: Univerzita Karlova v Praze.

Obr. 5 – Ekohydromorfologický stav toku Bíliny, hodnocené metodikami EcoRivHab (a) a LAWA-OS (b) do pěti ekomorfologických stupňů (1 – nejlepší, 5 – nejhorší). Data: Univerzita Karlova v Praze.

Obr. 6 – Změny ve specifickém odtoku plavenin v povodí Blšanky vyjádřené modely SWAT a AnnAGNPS; a – SWAT 1995–99, b – SWAT 2000–04, c – AnnAGNPS 1995–99, d – AnnAGNPS 2000–04.

Obr. 7 – Vývoj transportu plavenin ve vztahu k průtoku vody v profilu Holedeč na Blšance v období 1994–2007. Data: Univerzita Karlova v Praze.

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