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Tereza Beránková[ab]; Richard M. Vogel[c]; Daniel Fiala[a]; Pavel Rosendorf[a]
[a] Department of Water Ecosystems Protection, T. G. Masaryk Water Research Institute, Praha, Czech Republic [b] Department of Land Use and Improvement, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Praha 6 - Suchdol, Czech Republic [c] Department of Civil and Environmental Engineering, Tufts University, Medford, Massachusetts, USA

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Estimation of phosphorus loads with sparse data for agricultural watersheds in the Czech Republic

Tereza Beránková[1,3], Richard M. Vogel[2], Daniel Fiala[1] & Pavel Rosendorf[1]

[1]*Department of Water Ecosystems Protection, T. G. Masaryk Water Research Institute, PRI, Podbabská 2582/30, Praha 6 – 160 00, Czech Republic*
tereza_berankova@centrum.cz

[2]*Department of Civil and Environmental Engineering, Tufts University, Medford, Massachusetts 02155, USA*

[3]*Department of Land Use and Improvement, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamýcká 129, Praha 6 – Suchdol 165 21, Czech Republic*

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Abstract Agricultural watersheds in the Czech Republic are one of the primary sources of non-point-source phosphorus (P) loads in receiving waters. Since such non-point sources are generally located in headwater catchments, streamflow and P concentration data are sparse. We show how very short daily streamflow and P concentration records can be combined with nearby longer existing daily streamflow records to result in reliable estimates of daily and annual P concentrations and loads. Maintenance of variance streamflow record extension methods (MOVE) can be employed to extend short streamflow records. Constituent load regressions are used to predict daily P constituent loads from streamflow and other time varying characteristics. Annual P loads are then estimated for individual watersheds. Resulting annual P load estimates ranged from 0.21 to 95.4 kg year^{-1} with a mean value of 11.77 kg year^{-1}. Similarly annual P yield estimates ranged from 0.01 to 0.3 kg ha^{-1} year^{-1} with an average yield of 0.07 kg ha^{-1} year^{-1}. We document how short records of daily streamflow and P concentrations can be combined with a national network of daily streamflow records in the Czech Republic to arrive at meaningful and reliable estimates of annual P loads for small agricultural watersheds.

Key words total phosphorus; agricultural watersheds; MOVE; regression; correlation; load

Estimation avec des données éparses des charges de phosphore de bassins versants agricoles de la République Tchèque

Résumé Les bassins versants agricoles de la République Tchèque sont l'une des principales sources diffuses de phosphore (P) vers les eaux réceptrices. Puisque de telles sources diffuses sont généralement situées dans des bassins versants de tête, les données de débit et de concentration en P sont rares. Nous montrons comment de très courtes séries de débit journalier et de concentration en P peuvent être combinées avec des séries de débit journalier plus longues du voisinage, afin e produire des estimations acceptables des concentrations et des charges journalières et annuelles en P. Les méthodes d'extension de série de débit avec conservation de la variance (MOVE) peuvent être utilisées pour étendre les courtes séries de débit. Des régressions sont utilisées pour prévoir les charges journalières en P à partir du débit et d'autres caractéristiques variables au fil du temps. Les charges annuelles en P sont ensuite estimées pour des bassins versants particuliers. Les estimations obtenues de la charge annuelle en P varient de 0.21 à 95.4 kg an^{-1}, autour d'une moyenne de 11.77 kg an^{-1}. Les estimations de l'exportation spécifique annuelle de P varient de 0.01 à 0.3 kg ha^{-1} an^{-1}, autour d'une moyenne de 0.07 kg ha^{-1} an^{-1}. Nous explications comment de courtes séries de débit journalier et de concentration en P peuvent être combinées avec un réseau national de séries de débit journalier de la République Tchèque affin d'obtenir des estimations pertinentes et fiables de la charge annuelle en P pour des petits bassins versants agricoles.

Mots clefs phosphore total; bassins versants agricoles; MOVE, régression; corrélation; charge

INTRODUCTION

Phosphorus (P) plays a significant role in surface water eutrophication, since it often limits the growth of freshwater phytoplankton (Correll, 1998), and harmful cyanobacterial blooms present the most serious manifestation of eutrophication. Substantial reduction of

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phosphorus loads will be required to meet the high water quality standards set by the Water Framework Directive of the European Union. While various control measures have been successfully adopted for point sources of pollution the regulation of non-point sources is much more challenging due to difficulties associated with the identification of source areas, quantification of pollution and application of appropriate control measures. Thus increasing attention should focus on reduction of non-point pollution.

Agricultural land use is a significant non-point source of phosphorus. Phosphorus is transported mostly by surface or subsurface runoff in the dissolved and particulate phases. An important source of phosphorus is the soil itself, though the content of soil phosphorus varies among soil types and depends on the underlying geological formation. The natural content of soil phosphorus is further increased by fertilizer and manure application. Transport of phosphorus can be accelerated by inappropriate agricultural practices, due to increased soil erosion and/or due to excessive application of fertilizer or manure, or applications at the wrong time and/or place. An overview of phosphorus sources and transport from agricultural land is given by Hansen *et al.* (2001) and Hart *et al.* (2004).

A long record of soil testing in the Czech Republic indicates a significant relationship between fertilizer application and available soil P content. Intensive agriculture, promoted in less fertile regions and accompanied by large scale application of fertilizers especially in the 1970s and the 1980s, resulted in an increase of available soil P throughout the country (Central Institute for Supervising and Testing in Agriculture, 2009). Accordingly, after the political change in 1989, that was followed by economic transformation, the consumption of P fertilizers until now has decreased to up to 25% of the mean consumption prior to 1989 (Klement & Sušil, 2009). The consequent decrease of available soil P was not reported until the mid-1990s, but the later results of soil testing showed a decrease of available soil P on arable lands by an average of 5 mg kg^{-1} between 1993–1998 and 1999–2004 soil testing cycles (Klement & Sušil, 2005), and a further decrease by an average of 7 mg kg^{-1} between 1999–2004 and 2003–2008 soil testing cycles (Klement & Sušil, 2009). Despite these trends of available soil P levels, and improvement of point sources of phosphorus, the eutrophication of rivers and reservoirs remains a serious water quality problem.

In this study, we introduce a methodology for the quantification of annual total phosphorus (TP) loads in receiving waters associated with agricultural watersheds. We describe a procedure for estimation of constituent loads in rivers which have been subject to only sparse measurements of flow and P concentration. To avoid the influence of point sources, all study sites were located in agricultural headwater watersheds without any point source or permanent habitation. For such small watersheds, long periods of hydrological and water quality data are not normally available. High-frequency water quality and quantity sampling is often not feasible, because it requires significant financial and personnel resources. Instead, we introduce a cost-effective methodology which transfers hydrological information from nearby gauged watersheds, using regression methods. The idea is to develop a relationship between daily streamflow observations at gauged watersheds and daily streamflow observations at watersheds with sparse records, and then to use that relationship along with another relationship between streamflow and constituent concentrations to enable the extension of very short records of phosphorus and streamflow measurements into records that may be useful for planning purposes.

For small watersheds, most of the phosphorus is transported by surface runoff processes during rainfall events. Thus P concentration data should be collected at both fixed intervals and during rainfall–runoff events (Toor *et al.* 2008), which is demanding in terms of time, finance and work organization – similar to high-frequency sampling. Robertson & Roerish (1999) questioned the role of additional storm samples when estimating annual loads on small watersheds, because they can result in positive bias. Instantaneous concentrations measured during storm events are often two or more orders of magnitude higher than average daily concentrations. Storm sampling strategies during extreme events are useful for calibration of watershed models and serve well for the description of temporal patterns in water quality, but should be treated carefully if one's interest is only in estimation of unbiased annual loads (Robertson & Roerish, 1999; Robertson, 2003). Johnes (2007) evaluated various load estimation methodologies and the impact of sampling frequency on the uncertainty of resulting load estimates. She documents that higher uncertainty is associated with less frequent sampling and using individual P fractions rather then total P. She also found that basins with low baseflow index and high population density tend to have more uncertain load estimates, especially when these are based on infrequent sampling.

Typically, for small agricultural watersheds, both water quality and flow records are either unavailable, or extremely sparse. In such cases, it is possible to transfer hydrological information from nearby sites with long-term flow records and/or with high-frequency sampling by employing the cross-correlation between short and long records. Such information transfer techniques can be used both to fill in missing observations and to extend short flow records (Salas, 1993).

The primary goals of this study were: (a) to obtain reliable unbiased estimates of annual phosphorus loads for small agricultural watersheds in Central Europe; (b) to demonstrate the utility of regression methods for extending very short daily streamflow records using information transfer techniques by exploiting the cross-correlation with nearby long-term streamflow records; and (c) to demonstrate the utility of regression methods for estimation of daily phosphorus loads from short samples of P concentration combined with extended streamflow series for small watersheds with sparse flow and concentration data.

METHODS

Study sites and data collection

Fourteen watersheds distributed around the Czech Republic were studied using 20 sampling sites (Fig. 1). The watersheds exhibit only agricultural land use with primarily arable land, and none of the watersheds contains point or diffuse sources of pollution. The watersheds range in size from 16 to 575 ha with a mean watershed area of 198.6 ha. The watersheds represent various agricultural regions and the most commonly occurring soil types in the Czech Republic.

Phosphorus concentrations were obtained from grab samples together with instantaneous discharge measurements at monthly intervals at the study sites during 2007–2008, which yielded 24 observations of P and streamflow at each site. Samples were analysed to determine TP concentration. In order to extend these short streamflow records, long-term daily streamflow data at nearby gauges were obtained from the national monitoring network operated by the Czech Hydrometeorological Institute. Watershed boundaries were delineated in upstream areas above the sampling sites in ArcGIS 9.1 using contour line vectors derived from 1:10 000 maps. Watershed areas were then calculated in order to define TP yields (kg $ha^{-1}year^{-1}$) from computed annual P loads and watershed area. Statistical analyses were carried out using the SPSS statistical package.

Extension of short daily streamflow records

The goal here is to use streamflow record extension methods to create complete daily flow series over the period 2007–2008 from the 24 values of daily streamflow samples collected monthly at each study site. The idea is to exploit the cross-correlation between

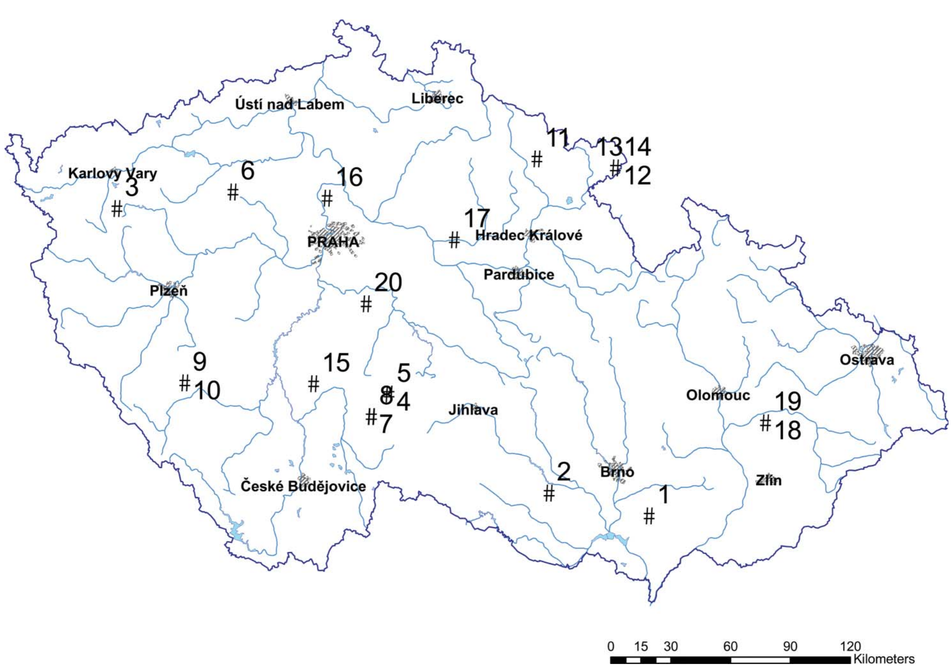

Fig. 1 Location of study sites in the Czech Republic.

the short flow records and nearby long-term index records. In order to find the best index station for each site, we computed the Pearson product–moment correlation coefficient between the logarithms of daily streamflow at the study sites and the various long-term potential index gauges in the vicinity of each site. The index station is chosen as that gauging station which exhibits the highest correlation between the logarithms of the corresponding flow series.

Once an index gauging station has been chosen, we employ the maintenance of variance extension (MOVE) method for extending streamflow records. This method assumes that the standardized logarithms of the daily flows are equal at both sites, so that:

$$\frac{y_t - \hat{\mu}_y}{\hat{\sigma}_y} = \frac{x_1 - \bar{x}}{s_x} \tag{1}$$

where y_t and x_t are the logarithms of the daily flows at the short and long record sites, respectively, $\bar{x}$ and s_x are the sample mean and standard deviation of the long x record and $\hat{\mu}_y$ and $\hat{\sigma}_y$ are specialized estimators of the mean and standard deviation of the short record, designed specifically to generate minimum variance and unbiased estimates of the extended values of daily streamflow at the short record site.

Various MOVE techniques were first suggested by Hirsch (1982), and later improved slightly by Vogel & Stedinger (1985) Grygier *et al.* (1989) and others, to reduce the bias and variance in estimates of the mean and variance of the flows at the short record site and to obtain a reasonable and unique extended streamflow record.

In general, all MOVE methods can be described by rewriting equation (1) as:

$$y_t = a + bx_t \tag{2}$$

The principle of MOVE methods is to derive estimates of the model coefficients a and b, in equation (2), that transform the long record x data into estimates of y in such a way that the theoretical moments of the estimated y values equal their true, but unknown values. In this study, we used the MOVE3 introduced by Vogel & Stedinger (1985) with the model coefficients a and b reported by both Vogel & Stedinger (1985) and Salas (1993).

The goodness-of-fit of the resulting daily streamflow extensions was assessed using the Nash-Sutcliffe model efficiency (NSE) (Nash & Sutcliffe, 1970). The NSE coefficient ranges from $-\infty$ to 1, with higher values generally indicating a better fit. Values of NSE < 0 indicate cases in which the extended sequence is a worse representation than if one were to simply report every extended streamflow using the sample mean of the short streamflow record.

Phosphorus load regression model development

Phosphorus concentrations and daily streamflows are often approximately described by a lognormal distribution and the logarithms of concentration and daily streamflow is often well approximated by a bivariate normal distribution (Clarke, 1990; Vogel *et al.*, 2005). Since loads are the product of concentration and flow, they may also be approximated by a lognormal distribution. Therefore, regression analysis between loads and flows is usually performed after logarithmic transformation of both variables.

Regression models of TP load for each site were developed assuming a linear relationship between the logarithm of loads and streamflow. This simple log-linear model can be further improved by accounting for nonlinearities, seasonality, censored data, time trends, and residual serial correlation (Helsel & Hirsch, 1992; Cohn, 1995). Further improvements may be possible if one were to employ the source apportionment models introduced by Bowes *et al.* (2008), who showed that the TP concentration–flow relationship differs significantly for diffuse and point sources of phosphorus delivery in a watershed. They showed that improvements in such regression relations are possible by dividing the watershed response into point and diffuse sources of P load.

Vogel *et al.* (2005) showed that the correlation between the logarithms of load and flow is always greater than the correlation between the logarithm of concentration and flow. This is termed a spurious self-correlation (Kenney, 1982) and results because load is the product of flow and concentration, thus load is functionally related to flow. Others have noted that, although this increased correlation is spurious, it may be useful in augmenting and extending a short record of load. The following multivariate linear regression was fitted at each site:

$$\begin{aligned}\ln(L) = \beta_0 + \beta_1 \ln(Q) + \beta_2 \sin(\omega T) \\ + \beta_3 \cos(\omega \mathrm{T})\end{aligned} \tag{3}$$

where L is the total phosphorus load in mg d^{-1}, Q is the daily discharge in dm^3 s^{-1}, T is the Julian day, $\omega = 2\pi/365$

and β_0, β_1, β_2 and β_3 are regression coefficients. The sin and cos terms account for the seasonal variation in behaviour of phosphorus loads. Other terms may be added to equation (3), such as a trend term; however, it was found that none led to model improvements.

Stepwise linear regression selection procedures were employed to determine, whether the seasonal factors led to improvements in the model. Regression performance was evaluated by using residual diagnostics to assure that model residuals were homoscedastic and approximately normally distributed. In addition, influence statistics were used to identify and eliminate outliers. Helsel & Hirsch (1992) summarize methods for development of such multivariate models, including a complete discussion of the model diagnostics employed in this study.

Once developed, load regression models for each site of the form shown in equation (3) were used in combination with the extended streamflow records to estimate a complete daily series of TP loads over the period 2007–2008 for all sites. Loads were then corrected for logarithm transformation bias introduced from the retransformation of the power-law model (Ferguson, 1986) by multiplying the resulting loads in real space by a bias correction factor (BCF), as suggested by Cohn (1995) and others. See Vogel *et al.* (2005) for further background on the behaviour of the BCF for such load regression models. The estimated daily loads were summed to calculate annual loads.

Finally, both MOVE and regression methods were cross-validated using a single year of data for estimating model parameters and the following year for validation. Values of streamflow and TP load for the second year were predicted and compared with actual values to determine the goodness-of-fit of the models.

RESULTS AND DISCUSSION

Streamflow record extension

As is often the case in practice, only a single daily streamflow measurement was available for each month at each site. These sparse daily streamflow records were extended by filling in missing values using the MOVE3 information transfer method from nearby gauges (see Vogel & Stedinger, 1985; Salas, 1993). The first step was to choose an index gauge for each study site using Pearson's correlation ρ between the logarithms of the daily streamflows at the study sites and various potential index gauges. The long record gauge y exhibiting the largest correlation with each short record site x was chosen as the index gauge for that particular short record site. Table 1 documents the correlations, which ranged from 0.86 to 0.99 with an average value of 0.91 for the 15 study sites. For the remaining five sites there were no index gauges with correlations above 0.8, which is considered the minimum correlation needed to transfer information (Vogel & Stedinger, 1985).

Once an index station had been chosen, the MOVE3 method was performed to extend the daily flow records at each site. To evaluate the MOVE3 method, we report the performance of MOVE3 for estimating the 24 reported values of daily streamflow which were available for each site. Here we used the Nash-Sutcliffe efficiency (NSE) as a measure of MOVE3 model performance with the results reported in Table 1. As expected, the values of NSE are proportional to the values of ρ. Values of NSE ranged from –0.18 to 0.95 with a mean value of 0.66. Only two sites exhibited such poor values of NSE, equal to –0.04 and –0.18, that we expect the MOVE3 method to perform poorly at those two sites.

Vogel & Stedinger (1985) and others have shown that the information transfer gains of MOVE methods

Table 1 Pearson's correlation coefficient ρ for correlation between logarithms of flows at study sites and nearby index gauges and Nash-Sutcliffe efficiency (NSE) of the model performance in streamflow simulation.

Site	1	2	3	4	5	6	7	8
ρ	0.95	0.87	0.90	0.95	0.94	0.86	0.96	0.88
NSE	0.92	0.26	0.75	0.93	0.81	0.78	0.91	0.86

Site	9	10	11	12	13	14	15
ρ	0.89	0.87	0.99	0.91	0.91	0.86	0.93
NSE	–0.18	0.68	0.95	0.79	0.72	–0.04	0.75

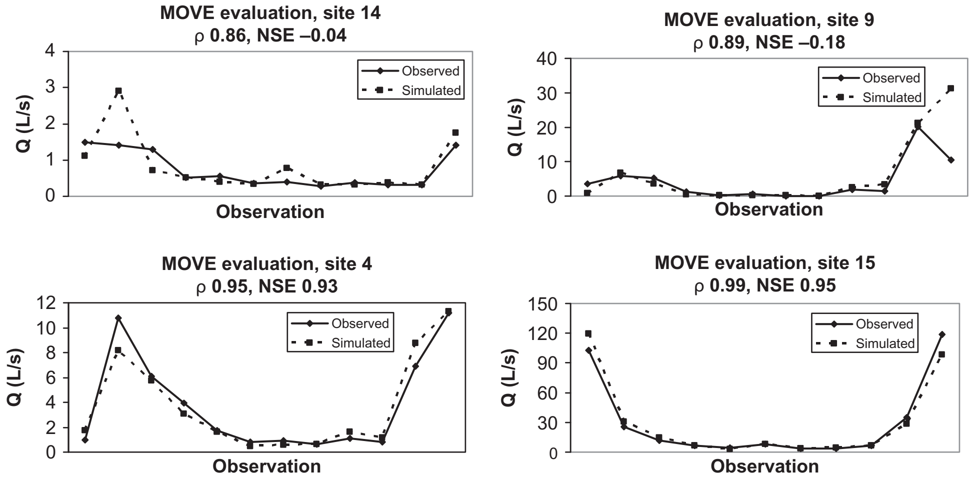

Fig. 2 Comparison of daily streamflow estimated using the MOVE3 method with observed daily streamflow for the two weakest and two strongest cases; the Pearson correlation coefficient (ρ) and Nash-Sutcliffe efficiency (NSE) are reported for each case.

are highly dependent on the strength of correlation (value of ρ) and on the length of the short record. Information transfer gains generally increase as either ρ increases and/or the number of observations in the short record increases. Vogel & Stedinger (1985) document that, as long as $\rho > 0.8$, information gains are to be expected, and that is the case for 15 of the sites considered in this study. Figure 2 compares values of daily flow prediction using the MOVE3 method with the 12 observed values for the two sites which had the highest NSE values, and for two sites which had the lowest NSE.

The index gauges are generally located on larger rivers than the study sites; thus, one might expect quite different hydrological behaviour among these rivers, yet we were able to find a suitable index gauge with sufficient correlation (ρ above 0.8) for 15 small watersheds out of 20 considered in this study. Perhaps this is in part due to the fact that the national monitoring network of streamgauges is relatively dense and operates in all regions of the Czech Republic.

Regression models of daily phosphorus loads

The primary goal of this study was to develop reliable estimates of annual TP load for all of the study sites considered for the study period. Regression models for the estimation of TP load were developed for each site using the streamflow and TP load observations during 2007 and 2008. Table 2 summarizes the models for

Table 2 Regression models for daily total phosphorus load (in mg d^{-1}) for each study site as a function of daily discharge, Q (dm^3 s^{-1}) and Julian day, T.

Site	Variables in the model	R^2	Adj. R^2	SEE%	Regression equation
1	$\ln Q$, $\cos(\omega T)$	0.893	0.884	73.3	$\ln L = 9.311 + 0.993 \ln Q - 0.814 \cos(\omega T) + \varepsilon$
2	$\ln Q$, $\cos(\omega T)$	0.746	0.731	57.3	$\ln L = 7.575 + 1.143 \ln Q - 0.745 \cos(\omega T) + \varepsilon$
3	$\ln Q$	0.953	0.950	56.3	$\ln L = 7.692 + 0.912 \ln Q + \varepsilon$
4	$\ln Q$, $\cos(\omega T)$	0.787	0.769	59.7	$\ln L = 8.266 + 1.101 \ln Q - 0.482 \cos(\omega T) + \varepsilon$
5	$\ln Q$, $\sin(\omega T)$, $\cos(\omega T)$	0.825	0.801	35.8	$\ln L = 7.373 + 1.254 \ln Q - 0.421 \cos(\omega T) - 0.313 \sin(\omega T) + \varepsilon$
6	$\ln Q$, T	0.634	0.600	43.3	$\ln L = 7.600 + 2.153 \ln Q + 0.002\, T + \varepsilon$
7	$\ln Q$	0.738	0.728	76.1	$\ln L = 7.349 + 1.091 \ln Q + \varepsilon$
8	$\ln Q$, $\sin(\omega T)$	0.924	0.911	44.2	$\ln L = 7.421 + 1.176 \ln Q - 0.502 \sin(\omega T) + \varepsilon$
9	$\ln Q$, $\cos(\omega T)$	0.923	0.915	76.0	$\ln L = 7.904 + 0.965 \ln Q - 0.708 \cos(\omega T) + \varepsilon$
10	$\ln Q$	0.955	0.953	53.0	$\ln L = 7.492 + 0.988 \ln Q + \varepsilon$
11	$\ln Q$, $\sin(\omega T)$	0.952	0.947	31.3	$\ln L = 8.442 + 1.247 \ln Q - 0.273 \sin(\omega T) + \varepsilon$
12	$\ln Q$, $\sin(\omega T)$	0.960	0.953	56.5	$\ln L = 9.213 + 1.222 \ln Q - 0.594 \sin(\omega T) + \varepsilon$
13	$\ln Q$	0.952	0.949	32.9	$\ln L = 9.094 + 1.045 \ln Q + \varepsilon$
14	$\ln Q$, $\sin(\omega T)$	0.985	0.984	12.2	$\ln L = 9.255 + 1.061 \ln Q - 0.112 \sin(\omega T) + \varepsilon$
15	$\ln Q$	0.668	0.652	73.4	$\ln L = 8.034 + 0.757 \ln Q + \varepsilon$

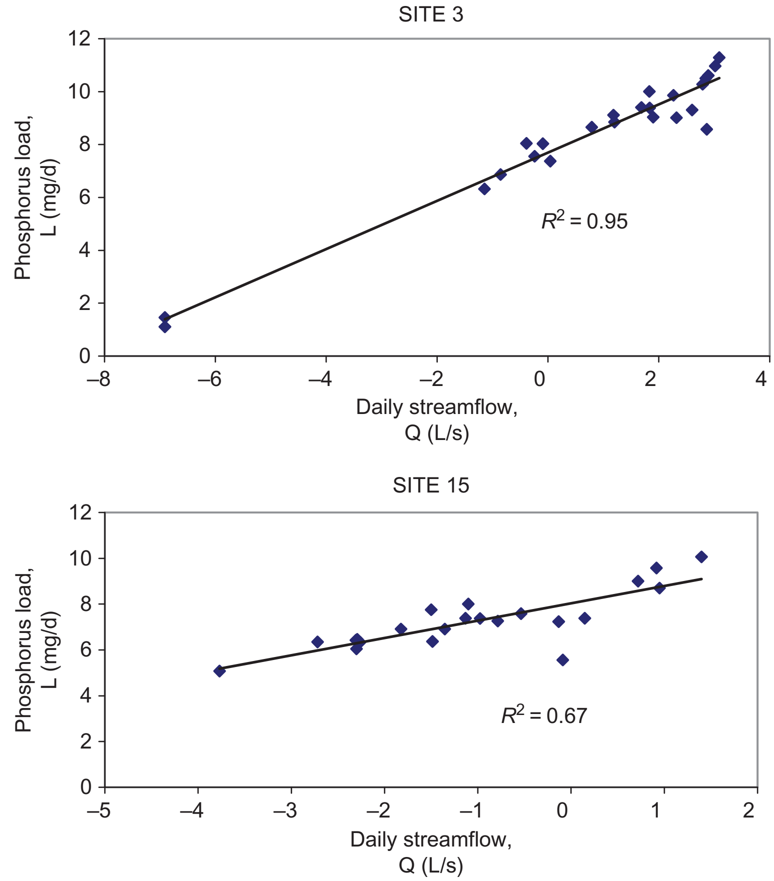

Fig. 3 Relationship between daily streamflow, Q, and daily phosphorus load, L (2007–2008), at two sites with high and low goodness of fit, respectively.

each site including independent variables, adjusted R^2, standard errors of estimate in %, and the final regression equations. The p values for all model coefficients were always below 0.01, except for a few values of the seasonal coefficients whose p values fell between 0.01 and 0.05. The adjusted R^2 values range from 0.60 to 0.98, with values above 0.9 in more than half of the cases. In all cases, the model residual, ε, was found to be approximately normally distributed.

Figure 3 illustrates two examples of the relationship between the logarithms of daily TP load and the logarithms of daily streamflow at two sites in which streamflow was the only independent variable chosen but which exhibit a wide range of goodness of fit. These two cases (sites 3 and 15) correspond to a value of R^2 equal 0.67 and 0.95, respectively.

Estimation of annual phosphorus loads

The regression equations reported in Table 2 were used to compute daily TP loads, given the extended records of mean daily streamflow generated using the MOVE3 methodology. Daily TP loads were corrected for bias and summed into annual loads. In some cases, summer droughts resulted in periods of zero streamflow at a few study sites, which posed a challenge because a logarithmic transformation is used in the TP load regressions. Therefore, annual loads were corrected by subtraction of daily loads which fell on days with observed zero streamflow. Annual TP loads ranged from 0.21 to 95 kg year^{-1}, and corresponding annual TP yields ranged from 0.01 to 0.3 kg ha^{-1} year^{-1}.

Model cross-validation

A split-sample cross-validation experiment was used to evaluate the credibility of the resulting TP load estimates. The performance of regression-based estimates of TP load and MOVE methods for streamflow record extension was validated by using data from 2007 to estimate model parameters, and those fitted models were then used to estimate streamflow and TP load values for 2008. The estimated values were then compared with actual values measured in 2008 and the

Table 3 Nash-Sutcliffe efficiency (NSE) for MOVE and regression cross-validation of streamflow and phosphorus load estimates for 2008.

Site	1	2	3	4	5	6	7	8
NSE (streamflow)	−21.72	−0.89	0.78	0.80	0.74	0.33	0.27	0.12
NSE (P load)	0.11	0.18	0.83	0.24	0.58	−3.2	0.19	0.35
Site	9	10	11	12	13	14	15	
NSE (streamflow)	−29.97	−11.46	−4.25	0.59	0.62	0.72	0.86	
NSE (P load)	0.50	0.45	0.87	0.75	0.73	0.93	0.65	

resulting NSE values are reported for each site in Table 3.

Values of NSE ranged from −29.97 to 0.86 (with a mean value of 0.33) for the MOVE method for streamflow estimates, and from −3.2 to 0.93 (with a mean value of 0.5) for the regression method for TP load estimates. Figure 4 shows the comparison of values of daily flow computed using the MOVE3 method with actual values measured in 2008, and Fig. 5 compares values of TP load prediction using the regression method with actual values measured in 2008. The cases which had the highest, the lowest and the average NSE values are reported.

The results show relatively good model performance of TP load prediction and streamflow extension, even for models based on a single year of observations. However, the performance of model predictions is expected to increase with the length of records. In some cases, seasonal time parameters entered the regression model based on only a single year of data, however we decided to exclude these parameters because they are likely to reduce the accuracy of the resulting TP load prediction. This is in accordance with Haggard *et al.* (2003), who discussed the effect of seasonal factors on prediction accuracy and suggested sufficient repetition of seasonal cycles when using seasonal time parameters in regression models. The regression model of TP load gives reliable estimates within the range of measured streamflow used for its development. Extrapolation beyond this range may influence the accuracy of predictions. The range of sampled streamflow used to develop the regressions corresponds to 95% of all daily streamflow values estimated for the study period. The remaining 5% (approximately 18 days per year) correspond to extreme events of high streamflow usually associated with soil erosion. Such extreme runoff with soil erosion is not fully captured by this approach, leading to potential underestimation of the annual TP load by as much as 50% or more (see Kalff, 2002). Thus, for future studies, the remaining 5% of daily TP loads corresponding to such extreme events should be considered separately, taking into account individual

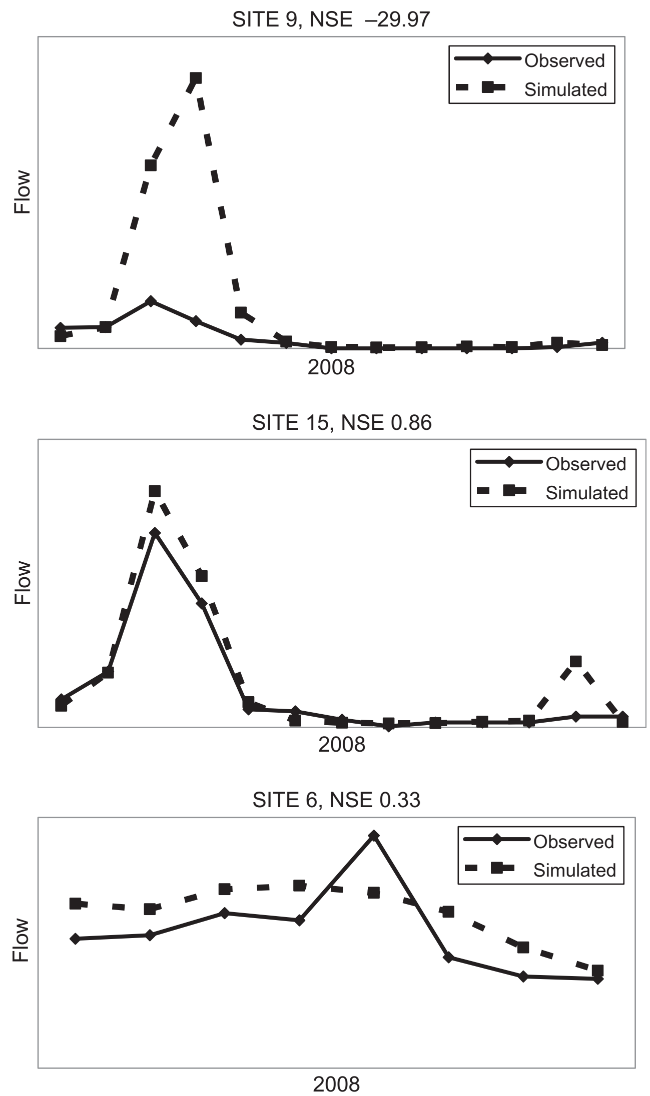

Fig. 4 Comparison of estimated daily streamflow with observed daily streamflow for the weakest, strongest and average cases with reported Nash-Sutcliffe efficiency (NSE) of the MOVE3 method.

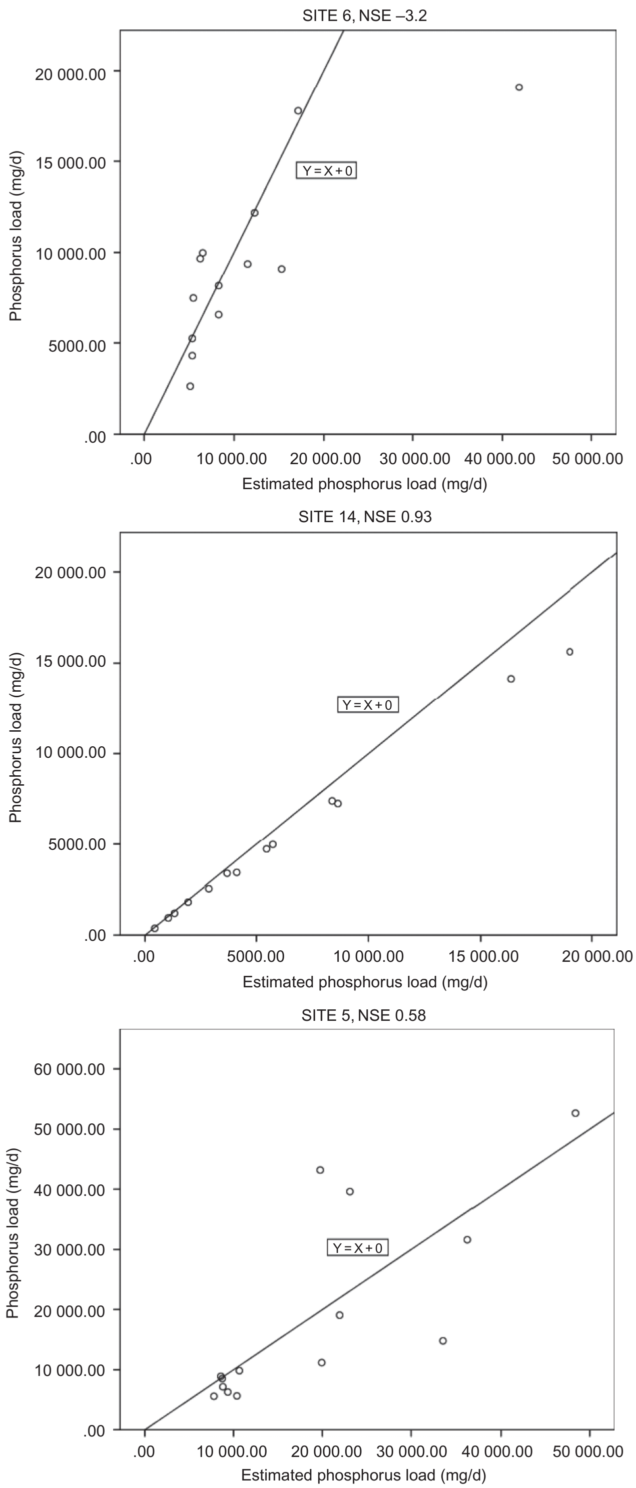

Fig. 5 Comparisons of estimated daily phosphorus loads with observed phosphorus loads for the weakest, the strongest and the average cases with reported Nash-Sutcliffe efficiency (NSE) of the regression method.

watershed characteristics, and the additional sampling during extreme events is recommended, where it is feasible.

CONCLUSIONS

We have illustrated how short records of daily streamflow and phosphorus concentration can be combined, by means of a national network of daily streamflow records in the Czech Republic, to obtain meaningful estimates of annual phosphorus load for small agricultural watersheds. Importantly, we performed a cross-validation experiment, which tested the ability of the resulting methodology to estimate annual phosphorus loads during a time period that was not used in the development of the model for predicting streamflow and/or phosphorus load. Such cross-validation experiments are essential to gain understanding of the credibility of a modelling approach. Our modelling approach is generally a statistical one, based on a unique concentration–discharge relationship for each catchment. Improvements to such P concentration–discharge relationships, such as those recommended by Bowes *et al.* (2008) and others, would likely generate associated improvements in resulting estimates of P loads using the methodology introduced here. We expect that other studies which only have sparse concentration records could benefit by exploiting regional streamflow information for the extension and/or augmentation of streamflow and concentration records in the Czech Republic, and possibly elsewhere.

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