# A GIS-based model for ditch erosion risk assessment in peatland forestry

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**Abstract** The maintenance of ditch networks in conjunction with peatland forestry increases erosion and suspended solid loads delivered to watercourses. Against this background, we tested a simple one-dimensional GIS-based steady-state hydraulic model for assessing erosion risk in forest ditch networks. Model accuracy and reliability were tested against experimental field measurements in two intensively drained peatland forestry catchments located in northern and central Finland. Despite the crude assumptions behind the simplified computational method, we found that low input data requirements, good visualization capabilities and short run times make the model a promising tool for informing water protection planning, although the spatial location of erosion risk simulated with the simplified model was not always consistent with the observed pattern of ditch erosion.

**Key words** peatland drainage; erosion risk; modelling; GIS; water protection

## INTRODUCTION

Ditch erosion and accelerated sediment delivery following routine ditch network maintenance are seen as key challenges for water protection in areas with peatland forestry (Joensuu, 2002; Marttila & Kløve, 2010). In Finland, an estimated 100 000 ha of the total drained peatland area of 5.7 M ha requires annual ditch maintenance (Finnish Ministry of Agriculture and Forestry, 2008). Ditching to assist managing peatland forests is also performed in regions other than Finland, including Fennoscandia, Russia, Great Britain, Ireland and South-East Asia (Paavilainen & Päivänen, 1995).

Numerous erosion models have been developed for the simulation of channel erosion and sediment transport (Merritt *et al*., 2003), but only a few specific models for peatland forest drainage areas have been proposed (e.g. Lappalainen *et al*., 2010). Application of the available channel erosion and sediment transport models to forest drainage areas is difficult due to complex ditch network structures and the large input data requirements of the models. For this reason, parsimonious computational approaches are needed to identify erosion risk areas for planning future ditch maintenance operations and allocating water resource protection measures.

Accordingly, a new GIS-based model for ditch erosion risk assessment was developed and tested. The main objectives of the work were: (1) to test the accuracy and reliability of the ditch erosion risk estimation, (2) to identify the main sources of error compromising model predictions, and (3) to assess the applicability of available GIS data for ditch erosion risk modelling.

## MATERIALS AND METHODS

### Model description

The ditch erosion risk assessment model tested by this study is a part of the RiverLifeGIS software that is included in the RiverLifeDSS decision support system (Lauri & Virtanen, 2002). Erosion risk is based on an interpretation of the results of a hydraulic model. The hydraulic model is a simple GIS-based model computational routine describing one-dimensional steady-state flow within the ditch network. This model simulates the spatial distribution of the steady-state ditch flow conditions using a predefined design runoff (L $s^{-1}$ $km^{-2}$) that enters the ditch network from its drainage area according to the estimated contributing flow and its accumulation. Based on the computed flow and velocity in the ditch network, the hydraulic model produces spatially-distributed ditch erosion risk assessment at the catchment scale. The model requires a raster-based digital elevation model (DEM) and the vector-based representation of water bodies, ditch network and catchment boundary.

The DEM is modified via merger with the ditch network vector mask and lowering the elevation of ditch pixels in the DEM so that runoff is forced to accumulate in the ditches and flow through the associated network. Using a pre-defined ditch profile, flow velocities and water depths within the ditch network are iterated by applying the Manning's equation ($v = n^{-1} R^{2/3} S^{1/2}$) and the average flow velocity ($v = Q\ A^{-1}$). Erosion risk assessment is based on the comparison of calculated flow velocities and local catchment areas in each of the 10-m units used to represent the ditch network (Table 1). For the erosion risk classification (Table 1), the boundary values for flow velocities were adopted from the scientific literature as being typical of the maximum permissible velocities for different soil types. The boundary values for the catchment area in Table 1 are based on the suggestions proposed by Leinonen (2009).

**Table 1** Classification of ditch erosion risk (after Leinonen, 2009).

| Erosion risk | Flow velocity (m $s^{-1}$) | Catchment area (ha) |
|---|---|---|
| No risk | <0.20 | |
| Moderate risk | >0.70 | 1–5 |
| | 0.45–0.70 | 5–20 |
| | 0.30–0.45 | 20–40 |
| | 0.20–0.30 | >40 |
| High risk | >0.70 | 5–20 |
| | 0.45–0.70 | 20–40 |
| | 0.30–0.45 | >40 |

In this study, DEMs were interpolated from the digital contour data in ArcGIS using the Topo to Raster tool. The resolution of the DEM was set to 10 m. The contour data for the DEM interpolation and the data for the input water bodies (rivers and lakes) and ditch networks were extracted from digital 1:20 000 topographic maps generated by the National Land Survey of Finland. Catchment boundary lines were added from the database of the Finnish Environment Institute (OIVA service on environment and geographic information). Before running the model, the Manning's roughness coefficient (*n*) was set to a value of 0.022, the design runoff (*MHq*) to a value of 100 L $s^{-1}$ $km^{-2}$, the ditch bottom width (*d*) to 0.25 m and the ditch bank slope (*s*) to 0.7.

## Field data collection and analyses

The model was tested against experimental field measurements in two intensively-drained peatland forests. Study area A1 (65°46.177′N, 28°19.113′E) was located in the catchment of Lake Kostonjärvi (F = 159 $km^2$) in northern Finland, and study area A2 (62°23.736′N, 27°7.906′E) in the catchment of the River Surnuinjoki (F = 41 $km^2$) in central Finland (Fig. 1). Initial ditching was carried out in 1962 and 1963, then maintenance in 1993 and 2006 in these study areas, respectively. Within study area A1, most of the ditches were excavated with 30–50 m spacing. A corresponding wider spacing of 65–80 m was used in study area A2. The average peat depth in study area A1 was 0.4 m (ranging from 0 to 1.2 m) compared with 0.3 m (ranging from 0 to 1.2 m) in study area A2, and in both areas, most of the ditches reached the underlying mineral soil.

Field measurements were performed during the summer of 2009. Erosion and sediment transport processes along the ditch networks were estimated by measuring the ditch cross-sections in different locations. Ditch bottom and bank erosion were qualitatively observed in both of the study sites by classifying ditches into four different classes. The interpretation of the magnitude of erosion in the ditches was based on the ditch size, vegetation cover, occurrences of ditch bank

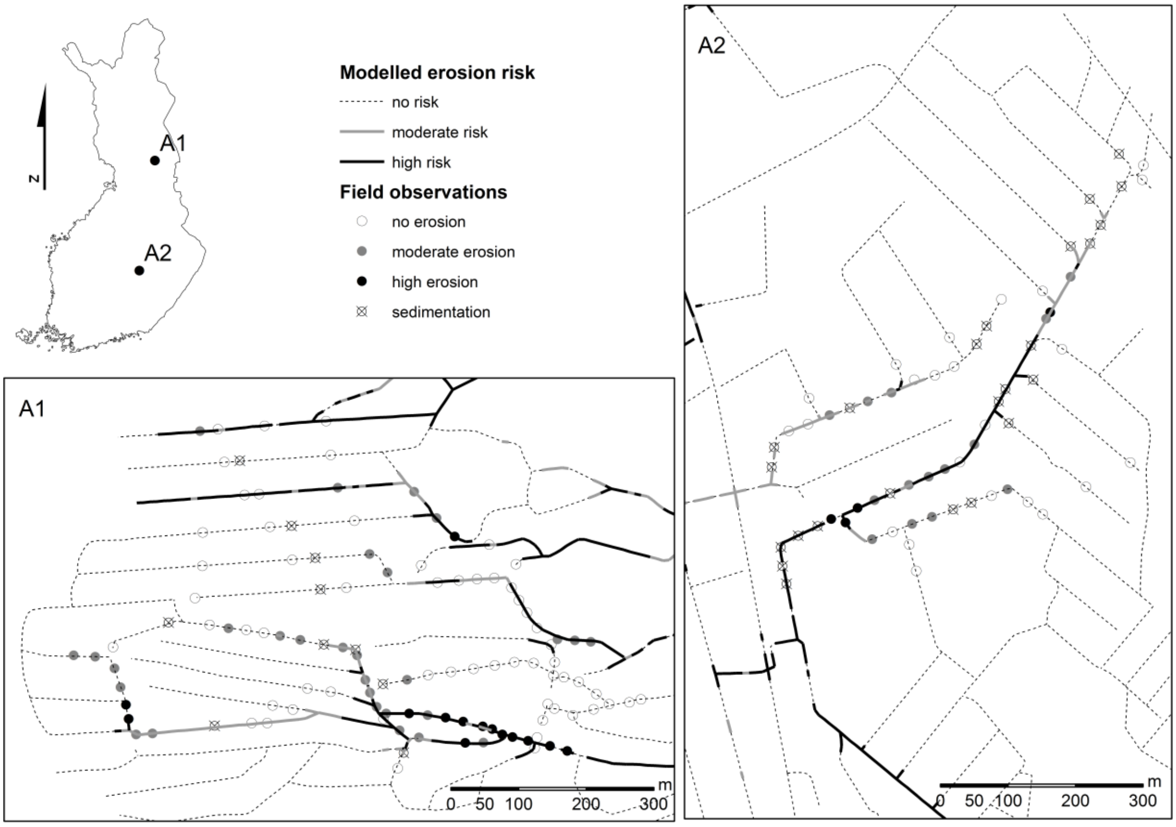


**Fig. 1** Overlay of the modelled erosion risk and field observations within the study areas A1 and A2. The structure of the ditch networks was corrected on the basis of the field observations.

collapse, and the particle size characteristics of the ditch bottom. Particle size distributions were studied by sieving the soil samples in the laboratory and by visual assessment under field conditions. Overall, data were collected from 112 points in study area A1 and 66 points in study area A2 at intervals of about 30 m on the basis of a systematic sampling strategy. Additionally, the spatial structure (e.g. joints and crossings) of the ditch network in each study area used as the model input was verified during the field observations.

Several statistical methods were applied to test the field data against the model predictions. Erosion risk estimation was tested by tabulating the calculated erosion risk and observed erosion using contingency tables. The model results were also visually compared with the field measurements by using overlay analysis in GIS. The sensitivity of the model to its input parameters was tested by analysing the cumulative distribution functions of the calculated flow velocities for the two study areas. Model sensitivity analysis was conducted by running the model several times for the study catchments with different initial parameter values. The accuracy of the DEM was tested by levelling the slope profile of a major ditch in study area A2.

## RESULTS

### The accuracy of the model input data

We found that the correct ditch network mask is essential for reliable modelling of ditch network hydraulics and assessing associated erosion risk. The observed ditch networks in the study areas A1 and A2 did not match perfectly with the ditch network mask extracted from the topographic maps and this resulted in inaccurate simulation of flow accumulation and ditch discharge. Ditch network structure is a major factor in the erosion risk estimation because the modelled flow velocities and local catchment areas are the only variables which affect the simulated erosion risk (Table 1). All observed inaccuracies in the initial ditch networks extracted for the study areas were corrected in refined model input data to support the assessment of model capability for predicting erosion risk.

The ditch levelling experiment in study area A2 revealed that the DEM utilised could not identify small-scale changes in surface topography. The resolution of the interpolated DEM was set to 10 m, but the quality of the contour data ultimately limited the actual DEM accuracy. The levelled ditch bottom and ground surface slopes agreed well with the observed erosion and sedimentation processes along the 800 m of the levelled ditch. Erosion had occurred on the steeper slopes along the ditch and sedimentation in the more level areas. Some of the errors in erosion risk estimation for study area A2 could therefore have been avoided with a more accurate DEM. The slightly inaccurate delineation of catchment boundaries affected model predictions in the outer parts of the study catchments, but the corresponding impact on model performance was small.

## Model performance and sensitivity

The model mostly predicted high or moderate risk of erosion for the main ditches where the simulated discharges were highest. Similarly, the model predicted no erosion risk for the smaller field ditches where the calculated discharges were lower (Fig. 1). This tendency results from the classification presented in Table 1. Significant small-scale variability in ditch erosion was observed during the field studies but could not be predicted by the model. The spatial resolution of the model did not support ditch erosion prediction at scales of less than 10 m. Erosion processes that were independent of water flow velocities were observed, and because these processes are not described in the model, they represent one of the sources of error in the predictions. For example, frost heaving and seepage erosion were both noticed to weaken ditch bank stability and thus increase the risk of severe erosion and sediment transport.

The measured ditch cross-sectional areas were regressed against simulated flow velocities and local catchment areas, but statistically significant relationships were not found. Based on the qualitative field observations of ditch erosion, the model was able to identify 40.4% of the observed high erosion risk areas and 76.7% of the observed no-risk areas within the study sites, when the default uncorrected ditch network masks were applied (Table 2(a)). The correction of the ditch network masks improved model performance and led to the correct prediction of erosion risk in 51.9% of the high erosion risk areas and 83.0% of the no-risk areas (Table 2(b)). The model overestimated erosion risk in almost 50% of the cases even after the correction of the ditch network masks. Model performance also varied significantly between the two study sites. For the measurement points where the model estimated high erosion risk, ditch erosion was actually observed in 56% and 44% of these cases in study areas A1 and A2, respectively.

**Table 2** Correlation between ditch erosion observations and the corresponding modelled erosion risks. Contingency tables are presented for (a) before, and (b) after the correction of the ditch network masks.

(a)

| Modelled erosion risk | Observed erosion | | |
|---|---|---|---|
| | No erosion | Erosion | Total |
| No risk | 66 (76.7%) | 20 (23.3%) | 86 (100%) |
| Moderate risk | 15 (50.0%) | 15 (50.0%) | 30 (100%) |
| High risk | 34 (59.6%) | 23 (40.4%) | 57 (100%) |
| Total | 115 (66.5%) | 58 (33.5%) | 173 (100%) |

P<0.05 (2-sided Pearson Chi-Square), $\chi^2$=8.915, C=0.221.

(b)

| Modelled erosion risk | Observed erosion | | |
|---|---|---|---|
| | No erosion | Erosion | Total |
| No risk | 78 (83.0%) | 16 (17.0%) | 94 (100%) |
| Moderate risk | 15 (48.4%) | 16 (51.8%) | 31 (100%) |
| High risk | 25 (48.1%) | 27 (51.9%) | 52 (100%) |
| Total | 118 (66.7%) | 59 (33.3%) | 177 (100%) |

P<0.001 (2-sided Pearson Chi-Square), $\chi^2$=24.003, C=0.346.

The cumulative distribution functions of the simulated flow velocities were studied to assess the sensitivity of the model predictions to perturbations in the values of the model input parameters (Fig. 2). It was found that the Manning's roughness coefficient *n* was the most influential parameter affecting the ditch network flow velocities and particularly the maximum velocities. The value of *MHq* had a clear influence on the calculated flow velocities but was less important than Manning's *n* for the computation of the maximum velocities. Ditch bottom width affected simulated flow velocities due to its impact on the ditch cross-sectional area ($v = Q\,A^{-1}$). The input value of the ditch bank slope affects the ditch cross-section profile but its importance for the flow velocity calculation was negligible due to the shallow flow depths in the study ditches. A given flow velocity was found to generate different erosion risk classification depending on the upstream catchment area.

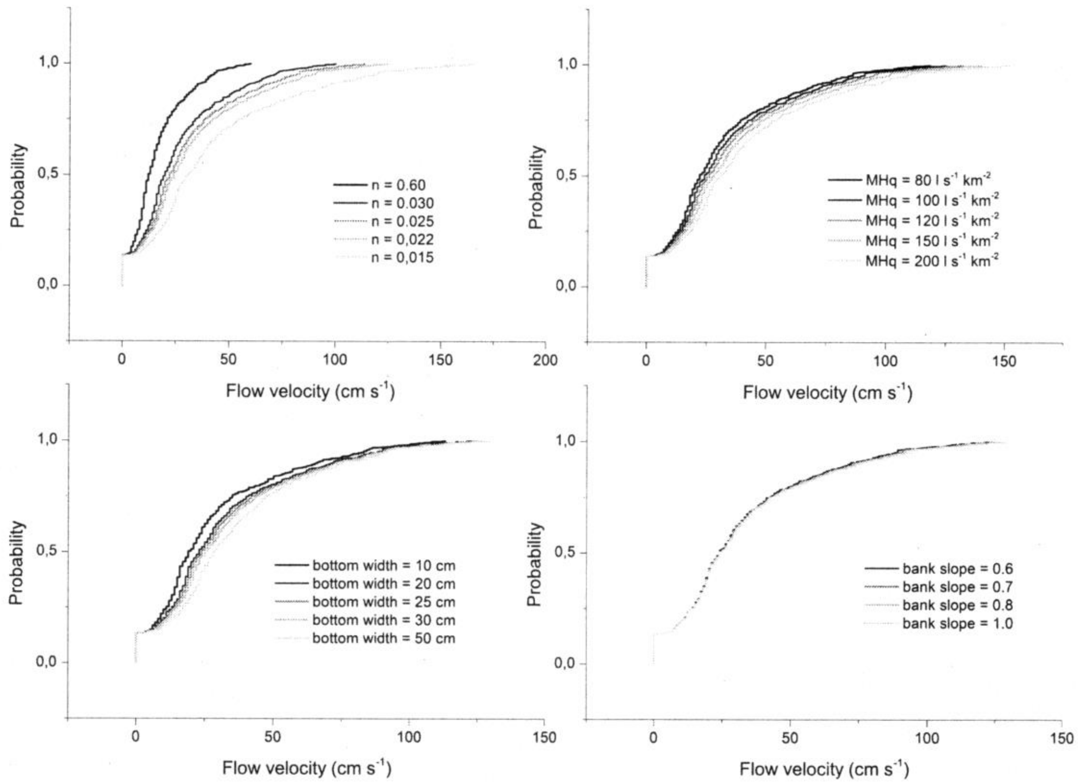


**Fig. 2** Cumulative distribution functions of the simulated flow velocities within study area A2. The values for the parameters were chosen on the basis of their typical ranges.

## DISCUSSION

Based on the experience and findings of this study, the parsimonious ditch erosion assessment model was found to have some advantages over more complex alternatives (Table 3). The suitability of the model for intricate ditch networks in large catchments and its low input data requirements are the main factors supporting the future development of the model. The work did, however, also identify several disadvantages which restrict the model's reliability and utility for ditch erosion risk estimation and the planning of ditch network maintenance (Table 3). Some of the disadvantages were related to the quality of the available input GIS data and thus cannot be eliminated by further developing the model structure or computational methods.

The accuracy of the input ditch network mask was found to have a significant impact on model performance. For this reason, the ditch network structure must be validated using field observations before the model can be applied. In large drainage areas this can be very time-

**Table 3** Model advantages and disadvantages.

| | Model disadvantages and sources of error | Model advantages |
|---|---|---|
| Input data | Ditch network<br>Catchment delineation<br>Digital Elevation Model | Minimum input data requirements<br>No need for parameter calibrations<br>Free software (GIS data usually not free) |
| Calculation method | Oversimplification<br>Erosion risk estimation method<br>Exclusion of precipitation – runoff processes<br>Exclusion of sediment transport processes<br>Steady-state calculation of flow velocities | Relatively short run times<br>Applicable to complex ditch networks<br>Good visualization<br>Results management and classification of model outputs for informing |
| Complexity of the phenomenon | Flow velocity independent erosion processes<br>Bank erosion<br>Vegetation growth and bed armouring<br>Erosion *vs* channel dimensions *vs* open channel hydraulics<br>Variation in soil types | Water protection planning |

consuming. If the ditch network design is revised to reflect actual erosion risk areas observed in the field, the updated network should clearly be used as model input to improve simulations. Significant erosion and sedimentation were observed within the study areas even in locations with a small local upstream contributing area. This challenges the use of catchment area as a parameter affecting ditch erosion risk estimation. Soil characteristics and local changes in ditch bottom slope are both likely to be more important factors than catchment area in affecting local ditch erosion risk. The failure of the current model to take account of variations in soil characteristics restricts model performance. We found that the measured cross-sections of the ditches were not correlated with the qualitative erosion observations. Due to local variations in surface topography and ditch excavation depths, we conclude that most of the small-scale changes in ditch cross-sections did not result from erosion or sedimentation processes. To detect erosion and sedimentation from the ditch cross-sections, the cross-sections should be measured before and after ditch network maintenance.

## GUIDELINES FOR FURTHER MODEL DEVELOPMENT

Improvement of the current GIS databases should be considered as part of the further development of the ditch erosion assessment model. Laser-scanned high-resolution DEMs are becoming more common and the potential for their use in ditch erosion risk modelling requires further investigation. The use of high-resolution DEMs would offer an opportunity to reassess the overall need for a vector-based input ditch network since this is a potential source of error in modelling ditch hydraulics and associated erosion risk. Ditch network structure and configuration could be defined directly from the high-resolution DEM. At the moment, the model reported in this contribution is not able to exploit GIS-based soil data. It is clear that soil characteristics should be included in the prediction of ditch erosion risk where suitable GIS data are available. Soil data could also be used for the estimation of the Manning’s roughness coefficient, and for more accurate calculation of flow velocities in the ditch network. The erosion risk assessment based on catchment area classification does not seem to be fully justified, and therefore requires further evaluation in the future.

**Acknowledgements** This study was funded by the Ministry of Agriculture and Forestry (HAME project), the Academy of Finland (ModStream project) and the RYM-TO doctoral programme. We would like to thank Drs Raimo Nevalainen and Jouko Saarelainen for their help with field measurements. Senior Research Engineer Hannu Lauri from EIA Ltd was consulted about the model structure and calculation methods.

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