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# Small-scale variability of the wind field over a typical Scandinavian lake

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Lake flow and transport models are largely dependent on the accuracy of the input data like wind forcing. In the current study the WAsP (Wind Atlas Analysis and Application Program) model was used for the calculation of wind conditions on a typical north European lake, lake Längelmävesi-Roine. Lake is relatively small and landscape fragmented. The main objective was to estimate how well the measurement made at one location represented conditions in different parts of the lake. It was found that, due to the influence of orography and surface roughness, the mean wind speed values could at certain locations be about 30% weaker than those at the measurement site. The variation in mean wind direction was small. The results of the study demonstrate that models like WAsP can provide valuable and substantial information and thus the use of wind models can improve the quality of lake model calculations.

## Introduction

EUROLAKES is an EU-funded research project that aims at improving strategies concerning the long-term management and short-term pollution control of deep European lakes and their catchment areas. For the project six lakes from different European countries were selected as study areas. In Finland, lake Längelmävesi-Roine, located in southwestern Finland, was selected as the lake for study. Within a few years about 500 000 people will get their daily drinking water from this lake, and this makes it important to monitor and also forecast the quality of its water. During summer there is a risk that the lake water quality will deteriorate temporarily due to cyanobacterial blooming in the lake. The traditional monitoring of cyanobacterial blooming is based on a few samples in space and time; however, there exist nowadays numerical computational models that provide an effective and fast way to assess the impact of various factors on transport and limnological processes (Falconer and Lin 1997, Inkala *et al*. 1997, Kiirikki *et al*. 1998). Models also enable one to get information from regions where observations are scarce. Models can also be used for prediction purposes.

As with other computational models, lake models are largely dependent on the accuracy of the input data. The most important input for hydrological models is rainfall and air temperature data, whereas for lake models wind data is of crucial importance. In hydrodynamic and limnological studies the meteorological data from the nearest meteorological observing station has typically been used. Some exceptions do exist, where a temporal lake station has been established for a certain project. Many lakes at high latitudes in Siberia, Scandinavia, Canada and Alaska are small. For example in Finland only about 1.4% of lakes are larger than one square kilometer (Raatikainen and Kuusisto 1990). Large unbroken open lake areas are rare, as the landscape is fragmented by islands, straits, bays and spits. The studies of Podsetchine and Schernewski (1999) and Schernewski *et al.* (2000) show how important it is to give the correct wind input for flow models, though this is a difficult task in a fragmented landscape.

The variation of wind speed over small lakes was studied by Venäläinen *et al.* (1998). They used the parameterization by Taylor and Lee (1984). The method was further slightly modified and programmed for PC-computers by Walmsley *et al.* (1989). According to the study, the sheltering effect has a large influence on wind speed on typical Scandinavian small lakes surrounded by forests. It is thus essential to take into account the location of the wind speed measuring location if point measurements are used, for example, for the estimation of area-integrated latent heat flux from the lake.

An example of wind field modelling over a larger lake can be found e.g. in Savijärvi and Järvenoja (2000). They used the High Resolution Limited Area Model (HIRLAM) mesoscale-type model to simulate the hourly-averaged climatology over Lake Tanganyika, located in the East African rift valley. The horizontal resolution in the model was 5.5 km. The results of that study were used by Podsetchine *et al.* (1999) for the development of a three-dimensional circulation model for Lake Tanganyika. Another study in the case of a large lake is the study of Beletsky (2001) He studied wind-driven circulation on the largest lake in Europe, Lake Ladoga, during episodes of strong wind. The grid size of his hydrodynamic model was 4 km and the model results can be used, for example, for analysis of biogeochemical data.

WAsP (e.g. Troen and Petersen 1989) is a well-known PC software package used especially for wind energy research. WAsP contains models for orographic flow perturbations, roughness changes, and the influence of obstacles on the wind field. WAsP has become a kind of standard in wind farm planning and the model has been used in several individual countries and also for larger areas for the production of wind atlases, e.g., Troen and Petersen (1989), Tammelin (1991), Frank and Landberg (1998), Reid (1997). Potentially the model can be also used for other purposes beside wind power calculations, such as the estimation of the wind field for lake current modelling in our case. Recently WAsP was tested for calculation of near surface winds at an agricultural site in southern Sweden. When compared with regression based techniques WAsP was found to give better results (Achenberger *et al.* 2002)

For lake modelling, the meteorological data from the nearest meteorological observing station has typically been used. In the current study, wind measurements were available from one measuring site on lake Längelmävesi-Roine. The main aim of the current study is to find out how representative the meteorological measurements made at one location on the lake are, i.e. can the point values be used for the modelling of wind-induced water currents in the lake? The modelling of the spatial variation of the wind field over the lake in this study was done using the WAsP software and the other aim of the study was to estimate the applicability of WAsP for purposes such as calculation of wind forcing in lake current modelling.

## Material and methods

### The WAsP model

The WAsP package contains models for orographic flow perturbations, roughness changes, and the influence of obstacles on the wind field. Based on a polar grid terrain representation, the orographic flow perturbations are evaluated as the sum of spectral potential flow solutions using a Fourier-Bessel expansion. For the vertical extrapolation to some new height above the surface in flat terrain with homogeneous roughness, a logarithmic wind profile is assumed. However, to account for the influence of non-neutral stratification, the logarithmic profile is perturbed. The homogeneous-terrain wind velocity is then modified by the above-mentioned terrain perturbations. All models depend on several parameters, which are described in Mortensen *et al*. (2000). The influence of orographic features like hills or more complex terrain on wind perturbations is calculated in the WAsP flow model by a method explained by Troen (1990). The model belongs to a group of models that are based on the theories of Jackson and Hunt (1975) and Taylor *et al.* (1983).

The wind data used for WAsP and other similar models can in principle also be taken from other sources than synoptic or similar weather stations. For example, the geostrophic wind based on measurements of surface air pressure, or the large-scale wind fields produced by different kinds of models describing the atmospheric circulation can be used. To get the local wind (or temperature, etc.) fields, meteorological variations have to be described in a more detailed form (smaller scale), especially in complex terrain.

WAsP is one of the models that has been verified against other models and field measurements (Walmsley *et al*. 1990). The models were found to be in good mutual agreement and generally also gave good results when compared with measurements. The largest expected errors in the results produced by WAsP are related to the calculation of the flow in a complex terrain. Empirically, the orographic model is found to work well for the prediction of flow perturbations over hills and ridges that are not too steep. The typical model-induced error is of the order of 10% in estimates of the relative increase of wind speed on the top of a hill that has horizontal dimensions of less than 1–2 km and slopes of less than 30%.

The orography of the study area was defined so that the isolines were at 84.2 m, 85 m, 88.3 m and 90 m and above that at 5 m intervals up to the highest point at 180 m above sea level. The roughness lengths were defined manually with the help of surface classification maps using the map editing facility of WAsP. The roughness of the different terrain types were: lake surface 0.0002 m, shoreline and low grassland 0.1 m, fields 0.3 m, small islands, rocks, bushes and short trees 0.4 m, forest and forested islands 0.5 m, tall forests and villages 0.7 m, towns 1.0 m. The roughness of the water surface in WAsP is constant at 0.0002 m. During development of the program an effort was made to use the well-known Charnock equation (Charnock 1955) in which the roughness of the water is dependent on wind speed. However, it turned out that the fixed value gave equally good results, so it has been used thereafter. In the case of relatively small lakes, the wave height is relatively low even during windy weather, so the use of a fixed roughness is hardly a serious limitation.

## Study area, measurements and calculations

Längelmävesi-Roine is a typical Finnish lake (Fig. 1). The surface area of the lake is roughly 150 km$^2$. The lake is situated near the city of Tampere and according to plans it will become within a few years the main source of drinking water for roughly 500 000 people living in the region. In Finnish lakes and coastal waters cyanobacterial species of the genera *Anaebaena, Microcystis, Nostoc* and *Oscillatoria* are typical (Pelander *et al*. 2000). The blooming of cynobacteria diminish the quality of the water, and this makes it important to be able to model and predict situations in which this may happen. Results of survey conducted in Finland between 1985–1987 (Sivonen *et al*. 1990) showed that 45% of 215 freshwater bloom samples were toxic. Usually blooming takes place at the end of summer under favourable meteorological conditions (hot dry weather) and sufficient supply of nutrients incoming from catchment areas of lakes and seas.

The Pirkanmaa Regional Environment Centre (PIR) conducted lake meteorological observations during the two summers of 1990 and 1991

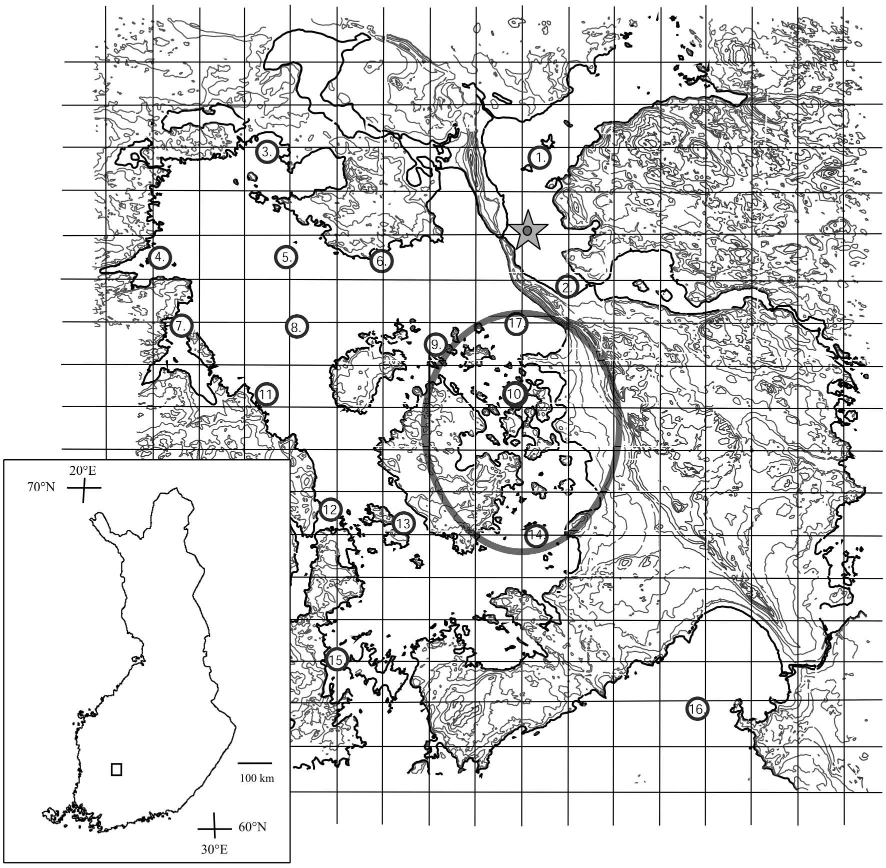



**Fig. 1**. The studied lake on the map of Finland and a topographic map of the area. The locations studied are numbered. The wind measurement site is marked with a star and the area of grid calculations is ringed. The size of the grid on the map is 1 km$^2$ and the elevation isolines are drawn at 5-m intervals.

near a place called Kaivanto channel (Fig. 1). In 1990 measurements were made 23.5.–19.7. and 4.9.–9.9. (altogether 8813 measurements). In 1991 measurements were made 13.6.–27.8. (altogether 21 689 measurement). The measurements included air pressure, air temperature, relative humidity, global solar radiation and wind speed and direction. The measurements were made at a height of two metres above the lake surface and values were ten- and five-minutes averages in 1990 and 1991, respectively. The instruments were installed on a float. The distance from the float to the shore was roughly 400 m towards the west, 700 m towards the north-east and more than 2 km towards the north.

For the study, 17 interesting locations (Fig. 1) in respect of lake current modelling were selected for analyses. The wind speed and direction at these locations was calculated using WasP on occasions when the wind speed at a height of 2 metres at the Kaivanto measuring site was either 5 or 10 m s$^{-1}$. Cardinal and half-cardinal point wind directions (i.e. 0°, 45°, 90°,… 315°) were studied. For each location a correction multiplier ($k$) was defined (Eq. 1) that relates the wind speed at Kaivanto (Kaivanto) and that at the locations of interest ($U$).

$$k = U/\text{Kaivanto} \quad (1)$$

Based on the Kaivanto measurements the wind climatology was calculated for the measuring site as well as for different locations over the lake. The seven most interesting study locations (1, 8, 10, 13, 14, 16 and 17) were selected for a more thorough analyses and the wind climatology of those sites was compared with the climatology of the Kaivanto measuring site.

The wind values measured over the lake were also compared with wind measurements made at a height of 14 m at Tampere-Pirkkala airport situated some 30 kilometres north-west of the lake measurement site. At Tampere-Pirkkala the measuring site is an open airport. The anemometer is located near the eastern end of the runway. The direction of the runway is 240/060 degrees. The forest there is about 10–15 metres tall and there are some buildings 5–12 m in height about

200–250 metres from the anemometer. In the direction of the runway, the landscape is more open; towards the south-west and the north-east the distances to the nearest obstacles are about 2.5 km and 1 km, respectively. Tampere-Pirkkala data were used as input in WAsP and wind direction frequency distribution and mean wind speed were calculated for the Kaivanto channel measuring site.

In addition to point studies, calculations were also made on a grid defined for an area situated in the eastern part of the lake. Inside this study sub-area there were numerous islands and thus the area was very fragmented. The grid-square size used in the calculations was 50 × 50 m. The wind speed at every grid square was calculated using WAsP on those occasions when the wind speed at the Kaivanto measuring site at a height of 2 metres was either 5 or 10 m s$^{-1}$. Cardinal and half-cardinal point wind directions were studied.

## Results

### Comparison of wind speed and direction as measured at Kaivanto and at Tampere-Pirkkala airport

The distance between the Kaivanto measuring site and Tampere-Pirkkala airport is about 30 kilometres and naturally there are some differences in wind speed and wind direction values. In the case of the Tampere-Pirkkala station 10-minute averages are available every 3 hours whereas in the case of Kaivanto the measured time-series is continuous. When Tampere-Pirkkala data were used as input in WAsP for calculation of mean wind speed at Kaivanto measuring site the mean simulated wind speed during the study period was 3.1 m s$^{-1}$ while it according to measurements was 3.0 m s$^{-1}$. The wind speed at a height of 14 metres at Tampere-Pirkkala airport was roughly as strong as the wind speed at the Kaivanto measuring site at a height of 2 metres. The water surface is smoother than the landscape at the airport.

According to measurements made at Kaivanto the most frequent wind direction was from sector 165–190° while it according Tampere-Pirkkala measurements should have been 135–165° (Fig. 2). There are several possible reasons for this difference: wind direction may be different due to weather conditions (low and high pressure area locations), orography and roughness may have some influence on wind direction and of course it is possible that either of the instruments has not been installed in quite the right direction. However, as the main interest of this study is to examine the spatial variation of wind over a lake this difference in wind direction is only an interesting “side product”.

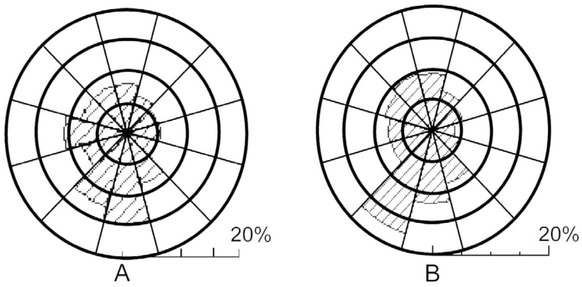



**Fig. 2**. The frequency distributions (%) of wind directions at the Kaivanto measuring site at a height of 2 metres above the surface (**A**) as estimated using WAsP and measurements made at a height of 14 m at Tampere-Pirkkala airport and (**B**) as measured at the Kaivanto measuring site.

### The wind climate at lake Längelmävesi-Roine

During the two study summers of 1990 and 1991, the prevailing winds were south-westerly (Fig. 3). South-west is the prevailing wind direction also according to long-term measurements (e.g. Alalammi 1987).

Based on the 1990 measurements made at Kaivanto, the wind direction frequency distributions were calculated for seven locations representing diverse conditions over the lake. According to the calculations, the wind direction frequencies at these locations do not differ from the values at Kaivanto.

When we looked at the mean wind speed from different directions (Fig. 4) we could see that for most wind directions the highest wind speed values were found at location 8 in the middle of the lake and the lowest ones at location 10, situated among small islands and quite near the shore. An interesting detail was found in the

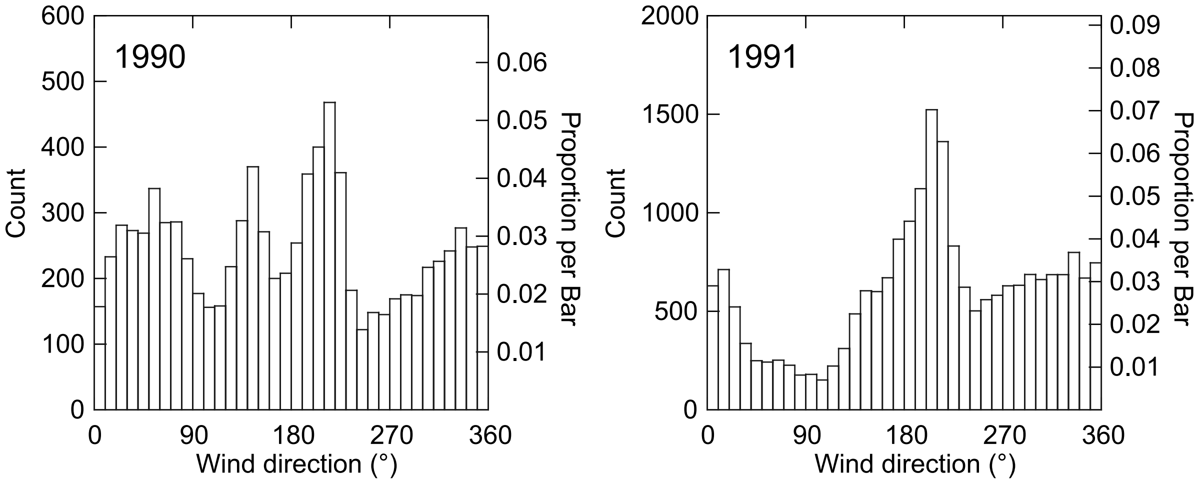



**Fig. 3**. The frequency distribution (%) of wind directions during the study period in 1990 and 1991 at the Kaivanto measuring site at a height of 2 metres above the surface.

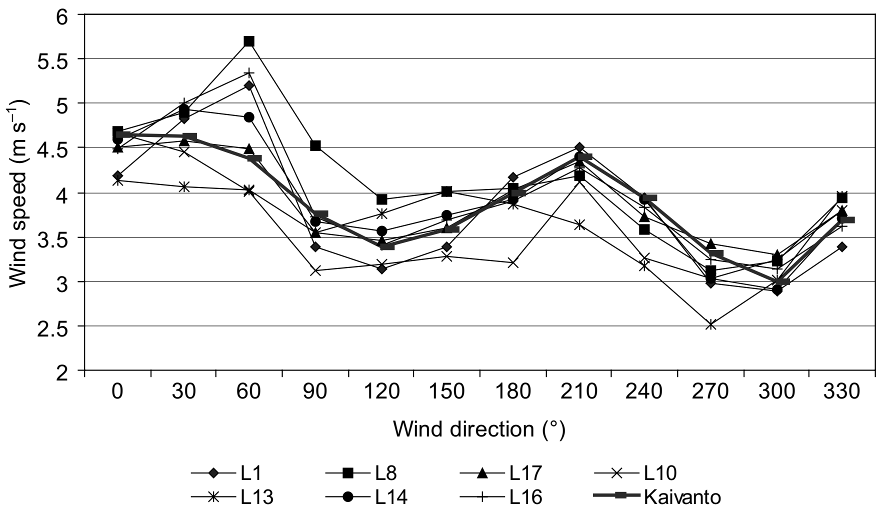



**Fig. 4**. Variation in mean wind speed (m $s^{-1}$) by directional sectors at seven study locations and at Kaivanto (Fig. 1) calculated using WasP, and measurements made at Kaivanto during summer 1990.

**Table 1**. The multipliers (*k*) that give the relation between wind speed values at the studied locations (Lo.) (Fig. 1) and those at the Kaivanto measuring site (Eq. 1). The values of *k* are given for different wind directions.

| Lo. | North | North-East | East | South-East | South | South-West | West | North-West |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.91 | 1.08 | 1.02 | 0.94 | 1.00 | 1.01 | 0.95 | 0.93 |
| 2 | 0.97 | 0.90 | 0.93 | 0.87 | 0.84 | 0.86 | 0.94 | 1.03 |
| 3 | 0.84 | 0.93 | 1.03 | 1.07 | 1.06 | 1.00 | 0.91 | 0.88 |
| 4 | 0.86 | 1.09 | 1.19 | 1.12 | 0.90 | 0.80 | 0.78 | 0.80 |
| 5 | 1.01 | 1.08 | 1.16 | 1.15 | 1.08 | 0.99 | 0.96 | 1.03 |
| 6 | 0.82 | 1.01 | 1.16 | 1.14 | 1.05 | 1.03 | 1.03 | 0.94 |
| 7 | 0.88 | 1.13 | 1.20 | 1.06 | 0.92 | 0.82 | 0.76 | 0.79 |
| 8 | 1.04 | 1.14 | 1.20 | 1.13 | 1.05 | 0.98 | 0.98 | 1.07 |
| 9 | 1.04 | 1.16 | 1.13 | 1.04 | 0.97 | 0.96 | 0.98 | 1.06 |
| 10 | 1.05 | 1.08 | 1.02 | 0.98 | 0.97 | 0.89 | 0.89 | 1.03 |
| 11 | 1.05 | 1.14 | 1.16 | 1.14 | 0.89 | 0.72 | 0.72 | 0.96 |
| 12 | 0.99 | 1.15 | 1.13 | 1.09 | 0.93 | 0.81 | 0.73 | 0.84 |
| 13 | 1.01 | 1.01 | 1.04 | 1.10 | 0.95 | 0.81 | 0.81 | 0.96 |
| 14 | 1.03 | 1.05 | 0.96 | 0.99 | 0.99 | 0.99 | 0.97 | 1.01 |
| 15 | 0.97 | 1.15 | 1.07 | 0.93 | 0.88 | 0.80 | 0.74 | 0.84 |
| 16 | 0.99 | 1.10 | 1.09 | 1.02 | 0.98 | 0.97 | 1.00 | 1.04 |
| 17 | 1.04 | 1.05 | 1.01 | 0.99 | 0.99 | 0.98 | 1.01 | 1.08 |

case of south-westerly and westerly winds, when the wind speed at location 8 was lower than at Kaivanto though the distance to the upwind shore is shorter in the case of the latter location. The explanation may be that the Kaivanto ridge is so narrow and low that it does not significantly influence the wind speed. Otherwise the results followed expectations; on the lee side and near the shore the wind speed was lower than in the middle of the lake.

## Representativeness of point measurements

In order to estimate how representative the Kaivanto measurements are at different locations over the lake, the wind speed and wind direction at 17 locations was calculated using WasP on those occasions when the wind speed at a height of 2 metres at the Kaivanto measuring site was either 5 or 10 m $s^{-1}$. Cardinal and half-cardinal point wind directions were studied. The values of the correction multipliers are presented in Table 1. Multiplying the wind speed value at Kaivanto by this figure allows one to make an estimate of the wind speed at the location of interest (Eq. 1). As the correction multiplier was only marginally dependent on the wind speed, the values in Table 1 are only given for the cases in which the wind speed at Kaivanto was equal to 10 m $s^{-1}$.

The wind speed values at locations 14 and 17 were closest to those at the Kaivanto measuring site. Relatively similar wind speeds could also be found at location 16. In the case of easterly winds, the Kaivanto measurements underestimated wind speed values at locations 4, 7 and 8 by roughly 20 per cent. When the wind was from the sector south-west to north-west then the Kaivanto wind speed values were about 20% higher than those at locations 4 and 7. The Kaivanto values were also relatively large overestimates in the case of south-westerly and westerly winds at locations 11 and 12. The difference was almost 30%.

## Calculations made on a grid

In this part of the study we examined how wind speed values can be estimated on a high-resolution grid. Inside the gridded sub-area there were numerous islands and the landscape was thus very fragmented. The grid square size used in the calculations was 50 × 50 m. The wind speed at every grid square was calculated using WAsP on occasions when the wind speed at a height of 2 metres at the Kaivanto measuring site was either 5 or 10 m $s^{-1}$. Cardinal and half-cardinal point wind directions were studied. A similar correction multiplier as that given in Table 1 for the specified locations was calculated for each grid square. To depict the variation of wind speed in the high-resolution grid, the wind speed values at the cardinal point directions are given in Fig. 5. One can see that the influence of large obstacles can easily be found several hundreds of metres downstream. For example, in the case of an easterly wind, the wind speed near the shore at the northernmost edge of the grid area was below 6 m $s^{-1}$. Over the open part of the lake the wind accelerates, so that after roughly 1 km the speed on the windward side of the first island was already around 12 m $s^{-1}$.

Another example of calculations made on a grid is given in Fig. 6. When the wind speed correction multipliers were calculated (Table 1), it was found that, in the case of south-westerly winds, the influence of the Kaivanto ridge was small, i.e. the wind speed at the Kaivanto measuring site was higher than, for example, that at location 8 situated in the middle of the lake. In Fig. 6, we can see that the maximum elevation of the ridge is about 25 m. The maximum wind speed (about 15.5 m $s^{-1}$) was found above the ridge, while the minimum values (about 7.5 m $s^{-1}$) were found just behind the ridge. As the ridge is narrow the wind speed already reached roughly the same value as that ahead of the ridge after a few hundred metres.

## The influence of orography and surface roughness on wind direction

According to the calculations made for the 17 study locations, the maximum turning of the wind due to orography and surface roughness was 2 degrees (Fig. 7).

At certain locations (L3, L5, L8, L9, L10 and L16), the wind direction was the same as

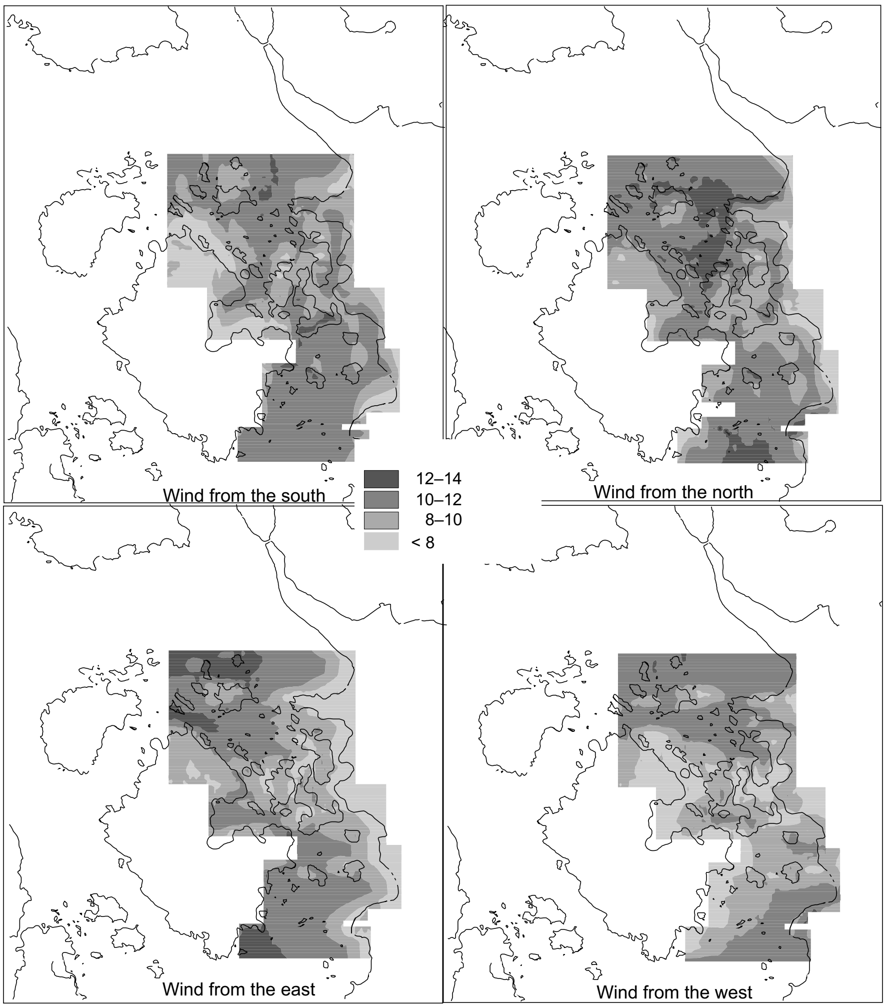
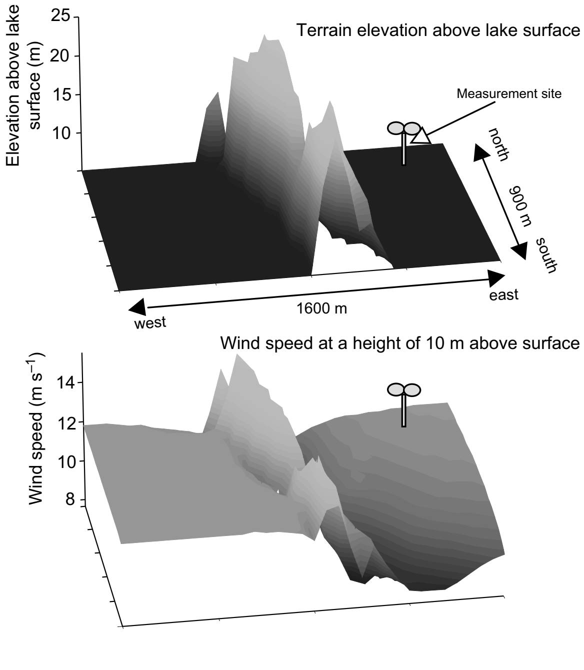



**Fig. 5**. Wind speed calculated on a 50 × 50 m grid at a height of 10 m in the case of the wind speed at Kaivanto measuring site being 10 m $s^{-1}$ and wind direction one of the cardinal points.




that at Kaivanto. The largest differences were to be found at locations L1 and L17. For example, at location L1 in the case of north-westerly, northerly, south-easterly and southerly winds the wind tend to turn clockwise towards open water, whereas in the case of north-easterly, easterly, south-westerly and westerly winds the wind tends to turn anticlockwise, also towards the direction where the over-water fetch had its largest value.

**Fig. 6** (left). The wind speed near the Kaivanto ridge at a height of 10 m above the surface calculated on a 50 × 50 m grid using WAsP. In the case studied the wind at the Kaivanto measuring site at a height of 2 m was from the southwest and the wind speed is 10 m $s^{-1}$. The measurement site is marked with an anemometer symbol.

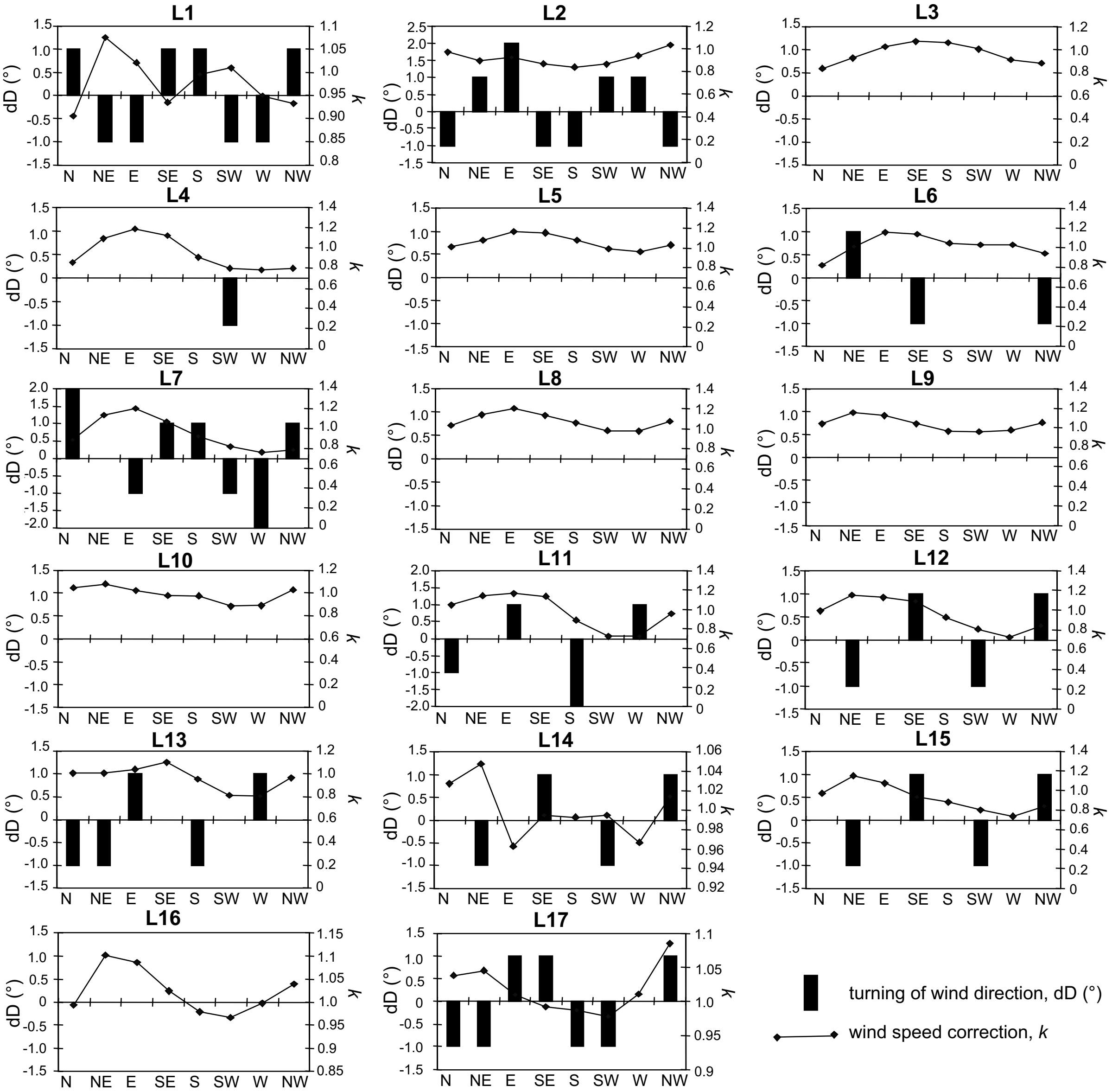



**Fig. 7**. The turning of the wind direction (dD) due to orography and roughness changes at 17 study locations (Fig. 2); in this case the wind direction at the Kaivanto measuring site was from a cardinal or half-cardinal wind direction. The wind speed correction multiplier is also shown in the same figure (Table 1).

## Discussion

The main aim of the study was to estimate the spatial variability of wind over a typical Scandinavian lake. The other objective was to test the use of WAsP model for this kind of calculations. The results indicate that at some studied locations and at certain wind directions wind speed was almost 30% weaker than at measuring location. On the other hand at some other locations wind speed was about 20% higher than at measuring site. These results depict the variability of wind speed on a heterogeneous lake and give valuable new information for lake modellers.

WAsP is a commercial software package and the use of model is relatively simple. However, one has to define the landscape accurately for the model and especially as the surface roughness is seldom available in a digital form a relatively large amount of preparatory work in digitising the surface characteristics is needed before the model can be run. Running the model for a large area covering several square kilometers using a high spatial resolution, with a grid denser than 100 meters, is relatively time consuming and calculation of wind field with an ordinary PC-computer can take several hours. In this sense linking this model dynamically with a lake model may be problematic.

## Conclusions

In this study we used the WAsP wind flow model for the calculation of wind conditions at different locations on a typical north European lake, lake Längelmävesi-Roine. The study area was roughly 150 km$^2$ and wind measurements were available from one location. The main objective of the study was to estimate how well the measurements represented conditions in different parts of the lake. It was found that, due to the influence of orography and surface roughness, the wind speed values could at certain locations be about 30% weaker than at the measurement site. The variation in mean wind direction at its maximum was only ±2%. It was also found that the effect of the narrow ridge near the measuring site extended to only a relatively short distance. The wind speed on the lee side of the ridge at a distance of about 500 m was almost as high as on the windward side of the ridge.

The main problem with the current study, as already indicated earlier, was that wind measurements were only available at one location on the study lake and thus verification of the results is not possible. However, the study demonstrates that the use of WAsP can be broadened to also cover applications other than wind power. For example, the use of models like WAsP for lake current modelling can provide important information about the spatial variation of the wind field over lakes and thus also improve the accuracy of lake water quality modelling.

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