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INTRODUCTION OF VEGETATION IN LARGE SCALE HYDRODYNAMIC MODELS

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A note from the author

The following document was made by Gonçalo Ferreira Cardoso, student at the *Instituto Superior Técnico – Universidade Técnica de Lisboa* in Civil Engineering – Hydraulics and Water Resources profile.
The work being reported in this document was made at *Lunds Tekniska Högskola – Lunds Universitet* in the spring semester of the academic year of 2004/2005, during which the author enrolled the Erasmus student exchange program.

The academic goal for this work is to serve as a final graduation project, also known as a degree project, worth 30 ECTS credits in a 5 year long graduation program.

The selected theme for the project was the introduction of vegetation in shallow lake hydrodynamic models, which can, in a wider perspective, be inserted under the subject of Lake Hydrodynamics, of simply Hydraulics, which is the area of interest of the author.

SUMMARY

Title: Introduction of vegetation in large scale hydrodynamic models

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Problem Definition: Vegetation is known to have different effects in shallow water environments, including changes in hydrodynamics. This often creates the need to include vegetation in large scale hydrodynamic models, which nowadays can already be achieved using some software packages available in the market.

This work, however, had the purpose to test simple methods to simulate vegetation in hydrodynamic models without having the need to use vegetation specific software.

Method: The tests were done using the MIKE 21 hydrodynamic module, developed by DHI Software, and two simple models were tested under different wind conditions. One of them simulated submerged vegetation by reducing the bottom depth as well as increasing the flow resistance values, while the other one, used to simulate emerged vegetation, consisted only of a significant increase in the flow resistance.

In order to validate the models and the results obtained some field measurements were made in a local shallow lake, Krankesjön, and it was possible to see that the emerged vegetation used was plausible and also a good approximation, which didn’t clearly happen with the emerged model. The current speed values obtained by the modeling were consistent with the values measured in the lake, always in the order of greatness of a few centimeters per second.

Results: The results obtained by the numeric modeling showed evident decreasing in the current speed values after introducing the vegetation models, along in some cases with changes in the preferential flow paths.

Conclusion: As an overall conclusion of the project, the submerged vegetation model showed to potentially be a good approximation to study hydrodynamics in shallow lake environments, even if used only as a preliminary study, while the emerged model didn’t prove to be so reliable. Some improvements and further tests are suggested to both models, in particular to the one for emerged vegetation, such as altering the wind friction values in the water surface over the areas with emerged vegetation to better approximate the real phenomenon.

Keywords: Vegetation modeling, Lake hydrodynamics.

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1 INTRODUCTION

Even though we might be used to think only of vegetation as the “green” that covers the landscapes, its presence in underwater environments is also quite significant, even if many times it can’t be seen. The diversity of plant species that can be found in aquatic environments is quite large, most of them being Macrophytes.

Macrophytes can be defined as large, vascular aquatic plants that grow in shallow water along the shorelines of lakes or in the slow-moving reaches of rivers (US Army Corps of Engineers – Link 1). Macrophytes can be submergent, emergent or floating (EPA – Macrophytes as Biological Indicators – Link 2), and some of the most common Macrophyte species are the water lily (floating), the stonewort (submergent) or the cattail (emergent), shown in Figure 1.

Some of these Macrophytes commonly found in lakes, such as the stonewort, can also be classified as Charopytes, the name given to freshwater algae (The Rhynie Chert Charophytes – Link 3).

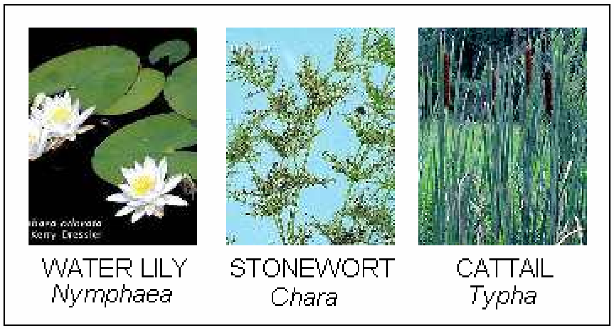

Figure 1. Macrophyte species (Lake Ecology – Primary Producers – Link 4)

Despite the fact of being a constant presence in most natural aquatic environments, vegetation gains particular relevance when considered in still or near still water settings, since it is necessary that the local hydrodynamics allow them to grow. Calm and stable environments, such as small shallow lakes, fulfill those needs, making them a good example of scenarios were the aquatic vegetation growth will be favored.

It is in fact quite common that ecosystems with submersed aquatic vegetation are shallow, and of moderate hydrodynamic energy (Teeter et al. 2001).

The generally accepted definition of a "shallow lake or pond" is that class of shallow standing water in which light penetrates to the bottom sediments to potentially support rooted plant growth throughout the water body. The lack of thermal stratification and the presence of muddy sediments are also common characteristics of this class of water. (Lake or Pond? What is the difference? – Link 5). As will now be explained, the presence of vegetation in these shallow lakes can be influential in several different levels.

1.1 Effects of vegetation

The immediate or maybe most obvious influence of vegetation in shallow lakes is probably the one to the fauna. Being a part of the natural ecosystem, the interactions of the vegetation with it will be to great extent, meaning for example that vegetation will be used as a source for both food and shelter by the surrounding species, as well as an important source of oxygen to the water mass (EPA – Macrophytes as Biological Indicators – Link 2).

Another also interesting perspective about the influence of vegetation in shallow lakes is the one that concerns the water quality, and even if at first it may not seem too obvious, the influence can be fundamental when it comes to this matter.

To begin with, vegetation has a great influence in the total suspended sediments, TSS, and therefore in turbidity, or how clear the water is. This is due to several effects, but mainly to the sheltering it produces, which can dramatically reduce the resuspension induced by the wind generated waves. This sheltering effect affects resuspension not only by protecting the bed sediments from being lifted, but also by inducing aggradation in them, which will increase their average size, and therefore make them less propense to be affected by the current (Teeter et al. 2001).
Another effect caused by the presence of vegetation, which amplifies the effect on water clearness, is the increasing of sedimentation (B.C. Braskerud, 2001). The main reason for this effect on sedimentation is a combination of reduced turbulence and reduced water velocity.

Overall, the combined effects of vegetation can originate a 40% decrease in resuspension when compared to the unvegetated scenario, as registered in B.C. Braskerud (2001).

Another important aspect about the ability of vegetation to influence the water quality concerns its power to remove pollution. Wetlands, for instance, are a good example of how vegetation can be used in the process of water treatment, and they are in fact quite common and efficient.

One of the most important steps in water treatment is the oxidation of the organic material, and vegetation has a great role in this when it comes to shallow waters. In fact, considering that shallow water environments are also typically environments of low to moderate hydrodynamic energy, the oxygen renewal by turbulent mixing is not as significant as in rivers or other hydraulic systems, so the oxygen released by vegetation through photosynthesis will be of greater importance. Oxygen is in fact of extreme relevance when it comes to water quality, and it is even commonly used as its main indicator, namely through the biological oxygen demand, BOD (A.J. Monteiro, 2003).

Besides having influence in the aspects discussed above, vegetation also has great importance when it comes to the hydrodynamics of the aquatic environment it is inserted in, which is the aspect that concerns this work the most.

To start with, one must keep in mind that vegetation can be present in a very wide range of densities, going from sparse or almost inexistent to very highly dense, making it difficult for any flow to occur. Having this in consideration, one can go trough some of the aspects in which vegetation affects the hydrodynamics of its surroundings, although they will necessarily depend on how dense the vegetation is.

The first and maybe most obvious effect of vegetation in hydrodynamics is related to the resistance it offers to flow. When compared to sand, mud, or other bed sediments, vegetation displays a much higher rugosity, which is due to the shape and volume of its parts (leaves and steams). This means that under the presence of vegetation the current will be slower than under a pure sediment bed, as the resistance to flow will be higher (considering typical lake bed sediments, of low volumetry).

Another effect of vegetation directly related to the bed conditions has to do with the shear stress. Since vegetation covers the bed sediments, the shear stress conditions under which the bed will be are necessary be different, which will also have an impact in on erosion, as vegetation will attenuate it (Teeter et al. 2001).

As described earlier, vegetation has an influence on the effects caused by the waves. But this influence will not simply be a decrease in resuspension they cause, as it will also affect the wave development itself. Shallow waters are environments in which waves will be highly affected by the bottom height, and therefore the presence of vegetation can result in a significant difference in the development of waves, which also has a direct effect on the local hydrodynamics. In fact, if the water depth is lower than the wave length divided by twenty, we will be in the presence of what is known as “small depths”, and the governing equations for the wave hydrodynamics according to the linear wave theory will be directly dependent of the water depth (I.M. Oliveira, 1985).

Depending a lot on the type of vegetation, as well as on its density, vegetation can also influence the overall layout of the current by creating preferential paths for water to go or short-circuits. These will most likely require dense vegetation and the effects can be easily be seen by evaluating the cell systems that typically occur in closed lakes.

Having in mind all of these effects that vegetation can have in shallow water environments, it becomes many times necessary to include its presence in hydraulic models, which can be run for many different purposes. The presence of vegetation can be quite influential in domains such as water storage in small dams, water treatment in wetlands, circulation in shallow lakes, or in a wider perspective, any potentially vegetated water environment, which are all good reasons to include vegetation in hydrodynamic models.

1.2 Purpose of this project

With the technology available nowadays one can find it to be quite simple to access powerful processing units and numeric models, which can already be set to include the presence of vegetation and take it into account in the processing, and use those for modeling.

However, it can also many times be good enough to use simple and less time and effort consuming hydrodynamic models, and simulate the presence of vegetation by changing a few of the model parameters accordingly, and still get significant results, without requiring accurate data and additional time to set the parameters of a real vegetation model.

In another perspective, simple vegetation modeling can be used to predict the necessity to further study the effects vegetation, and can therefore be used as a preliminary study.

The purpose of this work is thus to model the presence of vegetation in small shallow lake environments using simple techniques that can be used in most vertically integrated 2D models available in the market, and evaluate their potential to be used as a primary replacement for more advanced modeling techniques.

To fulfill the requirements of this work a research study has been necessary, mostly on lake hydrodynamics and circulation in shallow lakes, but also on the effects of vegetation in them, which have already been described. This was a necessary and important part of the project, as it helped to better understand the whole subject under study. Once this was done, the models were created and tested under different case scenarios using MIKE 21, a powerful modeling software. The choice of this particular software had mostly to due with the fact that it was the software available, but also due to its flexibility and graphical interface.

In parallel to the simulations made in MIKE 21 field measurements were also made in order to validate the models tested. These measurements were made at a small nearby shallow lake, the Krankesjön, and consisted of collecting current data, as well as wind data collected in the Stensoffa Ecological Station.

Finally, and having hold of both the modeling results and the values collected in the field, a brief discussion was made, including some suggestions for further studies and improvements to the models.

2 THEORETICAL BACKGROUND

2.1 Lake Hydrodynamics

To begin understanding the hydrodynamics of a lake, one must start by defining what a lake is.
A lake can be defined as a natural body of water wherein the water can be said to be “lentic”, i.e., slow moving when compared to rivers, created by the local topographic and hydrologic conditions (Henderson-Sellers, 1984).
Lakes are usually found in land depressions, where water will accumulate by confluence of runoff and mostly underground water. In fact, although lakes may have water intakes and outtakes, a general lake characteristic would be that the water exchanges with the exterior are usually not visible to the human eye. The typical water exchanges with the exterior in a lake would be on the underground level and by evaporation, hence without open flow exchanges.

Lakes can be used by men for many different purposes, which will typically include some kind of interaction with the water that induce its movement. Examples of these interactions would be water intakes or outtakes, like the ones used for water treatment in wetlands, as well as withdrawals for water supply, and others.

The water movements within lakes can have different origins, and usually the most significant ones are of natural origin, as are the wind-driven currents.

Wind-driven currents

The wind effect is of extreme importance to the current generation in lakes.
Wind-driven currents are initiated by the wind stress, which sets the lake water surface into motion. However, one must take into consideration other effects as well, such as the Earth’s rotation, sheltering effects, and boundary effects, which in fact are responsible for the need of two- and three- dimensional approaches for the study of Lake Hydrodynamics, and thus for the complexity of the phenomenon.

Such as in every other kind of water movement, the water circulation in lakes can be described by the three-dimensional Navier-Stokes equation, and also as usually done to study other kinds of flows, some significant simplifications can be made to the general equation (1) when considering lakes.

$$\frac{\partial u_j}{\partial t} + u_k \frac{\partial u_j}{\partial x_k} = -\frac{1}{\rho} \cdot \frac{\partial p}{\partial x_j} + \nu \frac{\partial^2 u_j}{\partial x_i \partial x_i} + g_i \tag{1}$$

Where:

u_j – velocity components;

t – time;

x_j – space coordinates;

ρ – water density;

p – pressure;

v – kinematic viscosity;

g – acceleration due to gravity.

The normal simplifications made to this equation for Lake Hydrodynamics are:

- To solve for the stationary, homogeneous case (∂/∂t = 0);
- To solve for the stationary stratified case;
- To solve for the temporal development of the current vector, u.

Solving the Navier-Stokes equation with such simplifications allows re-writing it as:

$$\frac{\partial w}{\partial t} = \nu \frac{\partial^2 w}{\partial z^2} - \frac{1}{\rho} \frac{\partial p}{\partial z} - g \tag{2}$$

Where w is the vertical component of the current vector.

Understanding the water circulation in lakes requires, however, the need for another equation, to ensure mass continuity. Combining this with the assumption of incompressibility, two statements will be originated:

$$\frac{\partial w}{\partial z} + \nabla \cdot u = 0 \qquad (3)$$

$$\frac{\partial p}{\partial t} + u \cdot \nabla \rho + w \frac{\partial \rho}{\partial z} = 0 \qquad (4)$$

Equation (3) relates the vertical velocity component to the current vector’s horizontal divergence, and equation (4) relates density variations, used in the non-homogeneous case.

An additional constrain that is often introduced is that of the “rigid lid”, which assumes that the water surface is completely still and horizontal. Under such assumption the surface displacement, ζ, will therefore become:

$$w(surface) = \frac{\partial \zeta}{\partial t} = \frac{\partial \zeta}{\partial x} = \frac{\partial \zeta}{\partial y} = 0 \qquad (5)$$

The mathematical solution of the system of equations outlined above can be solved once the boundary conditions are known, and several calculation models exist to solve them.

Mass transports

The mass transport problem is often solved using vertically integrated models, with which no consideration is taken on the vertical structure of the current. Solving this kind of models will provide a “global solution”, from which a posterior “local solution” can be obtained, consisting of the local velocity profile.

The components (U,V) of vertically integrated mass transports, **V**, are defined as:

$$\mathbf{V} = \left(U, V\right) = \int_{-H}^{\zeta} \frac{\rho u}{\rho_0} dz \qquad (6)$$

The transport equations can then be found in their linearized form by integrating the momentum equations, resulting as follows:

$$\frac{\partial U}{\partial t} - fV = -gH\frac{\partial \zeta}{\partial x} + F_x - B_x \qquad (7)$$

$$\frac{\partial V}{\partial t} + fU = -gH\frac{\partial \zeta}{\partial y} + F_y - B_y \qquad (8)$$

$$\frac{\partial U}{\partial x} + \frac{\partial U}{\partial y} = -\frac{\partial \zeta}{\partial t} \qquad (9)$$

These equations require the knowledge of F and B, which represent the bottom and the surface stress, respectively, in order to be solved. However, some simplifications can be made to them, for instance, by assuming that the Coriolis term, f, can be taken as a constant (if the basin is small enough).

As an example, solving the equations for the steady state homogenous current, assuming the Coriolis term to be constant, and neglecting the wind stress and bottom stress, these equations would provide the known *geostrofic balance*, if the y axis is chosen to be in the direction of the transport vector.

In fact, under these considerations, the equation system would become:

$$- fV = -gH\frac{\partial \zeta}{\partial x} \qquad (10)$$

$$0 = -gH\frac{\partial \zeta}{\partial y} \qquad (11)$$

$$\frac{\partial V}{\partial y} = 0 \qquad (12)$$

As shown in equation (10), this solution of the transport equations results in a balance between the pressure gradient force (α $\partial\zeta/\partial$x) and the Coriolis force (α fV), which is known as the mentioned *geostrofic balance*.

Solving the transport equations under different assumptions would, however, describe a different phenomenon. For example, considering a steady flow in which ζ = 0 everywhere, and where the bottom stress can be neglected, the concept of *Ekman drift* can easily be derived.

Another case would be the consideration of the flow well away from boundaries, for the case of $\zeta = 0$ in which the motion is a residual one following cessation of the wind. This would allow the time-dependent transport equations to be written as:

$$\frac{\partial U}{\partial t} - fV = 0 \tag{13}$$

$$\frac{\partial V}{\partial t} + fU = 0 \tag{14}$$

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{15}$$

Which have as solution for the transport components (considering the axis are aligned such that V = 0, U = U_0 at t = 0):

$$U = U_0 \cos ft \tag{16}$$

$$V = -U_0 \sin ft \tag{17}$$

In this case, the local solution would be:

$$u = \frac{U}{H_0} = u_0 \cos ft \tag{18}$$

$$v = \frac{V}{H_0} = -v_0 \sin ft \tag{19}$$

These equations, (18) and (19), describe the inertial response of the lake.

An interesting mass-transport related phenomenon that may also occur within lakes is the so called *coastal jet*. This occurs usually in large lakes, and consists of an enhancement of the water movement caused by vorticity generation. In such cases, the jet configuration may affect the termocline surface (if present), causing upwelling when the jet is from right to left (as seen by an observer looking out towards the lake) and vice versa. Under particular circumstances the presence of the jet may even lead to coastal entrapment of pollutants emitted to the near shore zone.

Vertical current profiles

As discussed earlier, the vertical current profiles are calculated as the local solutions from the mass transports global solutions. Different local solutions can be obtained under different assumptions, one of them being the Ekman drift.

The Ekman drift is a known phenomenon that relates the direction of the wind acting on a water body, and the corresponding current profile originated by it. The classical Ekman drift problem assumes an infinite water depth, and thus neglects bottom stress. This results is an downward logarithmic spiral-like vertical current profile, which vertically integrated will solve into a mass transport perpendicular and to the right (in the Northern Hemisphere) of the original wind vector. This phenomenon is responsible for currents known as *upwelling*, and under the conditions described, the angle between the surface current and the wind, ϕ, would be 45º.’

However, this model does not correspond entirely to reality. Observations show that ϕ is overestimated by the classical Ekman drift, and that, in fact, it depends on the acting wind speed. Several observations, such as the ones from George (1981) show a mean value of ϕ of 15.3º with highest deflections at lowest wind speeds. The relation between ϕ and the wind speed is therefore that higher wind speeds produce lower values of ϕ, which can be interpreted intuitively.

While studying shallow water lakes, it is most likely that the bottom stress will not be neglectible, and thus the vertical current profile may be significantly different from the one proposed by the Ekman drift. In many cases, however, simplifications can also be made to the vertical current profiles, typically resulting in 2D models. In this work, for example, the software used for modeling assumes a vertically homogeneous media, making it a so-called “2.5D” model with a uniform vertical current profile.

Waves and seiches

An important “side effect” phenomenon that may occur as a result of the wind action is the so called *seiche*.

Wind action can cause isobaric surfaces to tilt, resulting in an alteration in the surface level, and in a water accumulation near the boundaries opposite to the origin of the wind. This results in a increase of the water level, ζ, near these boundaries, known as the *wind set up*.

It is possible to measure the wind set up, which is in fact of great use, as under severe conditions the wind set up may cause significant damage on the shoreline. The measurement of the wind set up may therefore be a vital data for the design of coastal structures, and for the taking of safety measurements.

As the acting wind stops, it is common to observe a large period wave caused by the oscillation of the initially dislocated water mass. This particular wave is known as *seiche*.

As stated before, it is possible to estimate the wind set up, which usually depends on the local boundary conditions, and mostly on the incident wind.

2.2 Modeling

The complex nature of most physical phenomenon, allied with the necessity to predict the result of human interventions made in nature, has made it necessary to use physical models.

The usage of modelling to study a certain phenomenon has a strong security preoccupation behind it, as many of the human made interventions can somehow endanger lives or the integrity of the nature surroundings if unsuccessfully applied, but also, and also in a very strong way, by the need to intervene in an economic way, given the competition market we live in nowadays. Models should therefore ultimately be a way to study a certain phenomenon, understand it, and then be able to use the gained knowledge in a safe and economic way for the good of the community.

The main and basic assumption that physical models are used and built in, is that they are made to be representations of the real phenomenon being studied, and that the results obtained by modelling can later be extrapolated, at least partially, to what will happen in reality.

Physical models can be of different kinds, being reduced scale models and numeric models the ones of wider usage for civil engineering purposes.

Regardless of the kind of model being used, a physical model must always be a commitment between reality and the limits of our understanding and ability to reproduce it. Each kind of model has its own advantages and disadvantages, which means that the selection of the correct model to use must be carefully done.

Reduced scale models, for instance, have the advantage of including the real phenomenon in a lower scale, always involving the real 3D processes, and are most likely the most accurate way to reproduce a certain phenomenon. However, reduced scale models are expensive, they many times require long execution times – building a reduced scale model can be complicated and time consuming – collecting accurate data from them may not be easy, and more importantly, reducing the scale of the problem affects some of the physical variables. For this particular matter, when it comes to reduced models applied to hydraulics it is common to use certain parameters such as the Reynolds or the Froude number to ensure dynamic resemblance between reality and the model, although knowing that this will only apply to the relation between the specific variables described by the parameter being used, such as the relation between inertial forces, or gravity forces (A.C. Quintela, 1981).

Numeric models, on the other hand, are usually cheaper and faster, besides being able to reproduce reality in any scale, including the natural one. However, being numerical models, they are based in numerical solutions of the governing equations of the phenomenon they are being used for. This means in one hand that they are solutions to equations that by themselves are ways to explain reality with some approximation, but additionally, they use approximated methods to solve these equations, by assuming additional simplifications, or even by using finite methods to solve complex continuous equations.

It is then the task of the modeller to understand the limitations of each modelling option available to him, and do the best choice, often having to compromise between what is desirable and what is possible (Teeter et al. 2001).

Hydrodynamic models are no exception to these rules, which means that the modeller always plays an important role when deciding which assumptions to make. This is a task that obviously requires skill, experience, and often a-priori knowledge on the part of the modeller.

Hydrodynamic numerical modelling

In the particular case of this work, the selection on the type of model was necessarily of a numeric model (using specific software), as that was part of the works aim in the first place.

Hydrodynamic numeric models, such as most other types of spatial models, require geometric flexibility, high-dimensional representation and computational efficiency in order to be useful and reliable. Being approximations to the real scenario they must be adjustable to irregular bathymetries using grids or meshes in such a way that they can be accurate, which by itself leads to different modelling solutions.

The grids usually used in these models (see Figure 2) can be simple or multigrid, they can be structured or not, and use different indexation methods, like the hierarchical quadtree grid generation suggested in Borthwick et al. (2001). Mesh solutions are also possible, although they tend to require higher computational resources capability.

Regardless of what kind of bathymetrical support is used, hydrodynamic numeric models are always based is solving the governing equations under some assumptions. For example, the basis for governing flow equations is the 3D Navier-Stokes equations, which can be solved, for instance, assuming hydrostatic pressure distributions or water incompressibility (Boussinesq assumption). This will then originate simpler problems, which however must be ensured not to be too far away from reality.

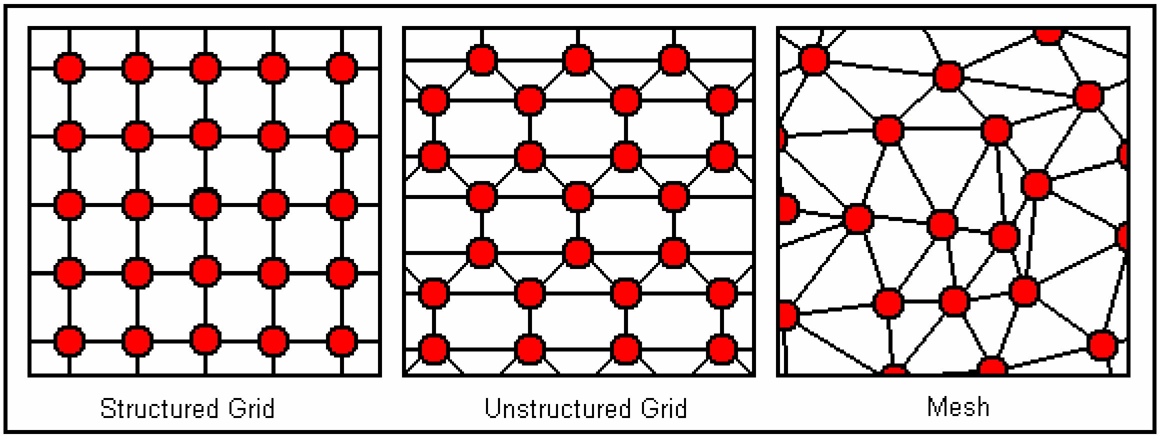

Figure 2. Topography/Bathymetry models.

The next step in hydrodynamic numerical models, after the initial assumptions, will be to solve the equations. Even here different methods can be used, also depending on the type of equation to be solved. Integral equations, for example, can be solved either as integrals or as the correspondent initial value problems for differential equations, which can be solved using finite difference methods. On the other hand, finite element methods can also be used to solve boundary value problems which are good solutions when using grid systems.

In the end this will lead us to many possible models for each situation, which can be either created specifically for the problem being studied, or simply recur to the use of pre-built models that will adapt to each scenario, such as most commercial software solutions. That was the choice for this project, being MIKE 21 the software used.

MIKE 21 HD – Hydrodynamic Module

MIKE 21 is a software application developed by the Danish Hydraulic Institute, DHI, that is part of a wider software pack, known as MIKE. MIKE contains applications and modules that allow modelling for most hydraulic related phenomenon, including 1, 2 and 3 – dimensional approaches for most of them. In this particular case, since the aim was to test two different vegetation models in larger scale hydrodynamic models, the choice was to use the MIKE 21 HD, the hydrodynamic module of MIKE 21.

The following description of the MIKE 21 HD software is based on the online documentation available on the DHI software website.

MIKE 21 HD is the basic computational hydrodynamic module of the entire MIKE 21 system, providing the hydrodynamic basis for other MIKE 21 modules such as for Advection-Dispersion (AD), ECO Lab, Particle tracking (PA) and Sediment Transport (ST, MT).

MIKE 21 HD simulates the water level variations and flows in response to a variety of forcing functions in lakes, estuaries, bays and coastal areas. The water levels and flows are resolved on a rectangular grid covering the area of interest.

MIKE 21 HD includes formulations for the effects of:

- convective and cross momentum
- bottom shear stress
- wind shear stress at the surface
- barometric pressure gradients
- Coriolis forces
- momentum dispersion (through e.g. the Smagorinsky formulation)
- wave-induced currents
- sources and sinks (mass and momentum)
- evaporation
- flooding and drying

Basic Equations

The hydrodynamic model in MIKE 21 is a general numerical modelling system for the simulation of water levels and flows. It simulates unsteady 2D flows in one layer (vertically homogeneous) fluids.

The following equations for the conservation of mass and momentum are integrated over the vertical to describe the flow and water level variations:

Continuity

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \tag{20}$$

x-Momentum

$$\begin{aligned} &\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial x}+\frac{gp\sqrt{p^2+g^2}}{C_2 \bullet h_2} \\ &-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}\left(h\tau_{xx}\right)+\frac{\partial}{\partial y}\left(h\tau xy\right)\right]-\Omega q-fVV_x+\frac{h}{\rho_w}\frac{\partial}{\partial x}\left(p_a\right)=0 \end{aligned} \tag{21}$$

y-Momentum

$$\begin{aligned} &\frac{\partial p}{\partial t}+\frac{\partial}{\partial y}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial y}+\frac{gp\sqrt{p^2+g^2}}{C_2 \bullet h_2} \\ &-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}\left(h\tau_{yy}\right)+\frac{\partial}{\partial y}\left(h\tau xy\right)\right]-\Omega q-fVV_y+\frac{h}{\rho_w}\frac{\partial}{\partial y}\left(p_a\right)=0 \end{aligned} \tag{22 }$$

Where:

$h(x,y,t)$ – Water Depth;

$\zeta(x,y,t)$ – Surface Elevation;

$p,q,(x,y,t)$ – Flux densities in x- and y- directions;

$C(x,y)$ – Chezy resistance;

g – Acceleration due to gravity;

$f(V)$ – Wind friction factor;

$V, V_x, V_y(x,y,t)$ – Wind speed and components in x- and y- directions;

$\Omega(x,y)$ – Coriolis parameter, latitude dependent;

$p_a(x,y,t)$ – Atmospheric pressure;

τ_{xx}, τ_{xy}, τ_{yy} – Components of effective shear stress.

The application of the implicit finite difference scheme results in a tridiagonal system of equations for each grid line in the model. The solution is obtained by inverting the tridiagonal matrix using the Double Sweep algorithms, a very fast and accurate form of Gauss elimination.

The implicit scheme is used in MIKE 21 in such a way that stability problems do not occur provided that the input data is physically reasonable, so that the time step used in the computations is limited only by accuracy requirements.

Input Data Requirements

The necessary data can be divided into several groups as briefly described below.

Basic Model Parameters

- Model grid size and extent
- Time step and length of simulation
- Type of output required and its frequency

Calibration Factors

- Bed resistance
- Momentum dispersion coefficients
- Wind friction factors

Initial Conditions

- Water surface level
- Flux densities in x- and y-directions

Hydrographic boundary conditions can be specified as a constant or variable (in time and space) level or flux at each open model boundary, as a constant or variable source or sink anywhere within the model, and as an initial free surface level map applied over the entire model.

Application Areas

MIKE 21 HD can be applied to a wide range of hydraulic and related phenomena. This includes modelling of tidal hydraulics, wind and wave generated currents, storm surges and flood waves. It can be a very important tool for hydraulic and hydrodynamic related problems, adding in the determination of design parameters used in coastal protection works as well as for offshore structures and sub sea pipelines. As mentioned previously, the MIKE 21 HD output results are also used as input for many of the other MIKE 21 modules such as the Advection-Dispersion module (AD), the Sediment Transport (ST, MT), the Particle tracking (PA) and the ECO Lab module.

As MIKE 21 HD is a very general hydraulic model, it can easily be set up to describe specific hydraulic phenomena. Examples of such applications are:

- tidal exchange and currents
- storm surge
- secondary circulations, eddies and vortices
- harbour seiching
- dam-break
- tsunamis

Solution Technique

The equations are solved by implicit finite difference techniques with the variables defined on a space staggered rectangular grid. A 'fractioned-step' technique combined with an Alternating Direction Implicit (ADI) algorithm is used in the solution to avoid the necessity for iteration. Second order accuracy is ensured through the centering in time and space of all derivatives and coefficients. The ADI algorithm implies that at each time step a solution is first made in the x-momentum equations followed by a similar solution in the y-direction.

3 CASE SCENARIOS

Considering the most common types of vegetation in shallow water environments, two vegetation scenarios were used in this work.

One of them consisted of simulating the presence of submerged vegetation, such as the Charophytes displayed in Figure 3. Submerged vegetation is an important part of the natural ecosystem in any lake, as it provides food and shelter for the fish species, as well as oxygen that is released in the water, among other effects previously explained.

Figure 3. Charophytes. (J. Clayton - Link 6)

Submerged vegetation can exist in any kind of density, and it will change quite a lot with the weather and the seasons of the year. In this case, it was decided to model highly dense vegetation, in a relatively high state of development. The reason to model submerged vegetation under these assumptions was that this way the results would represent a state of vegetation were one could expect a significant influence in the flow. Furthermore, the field measurements showed that these assumptions were quite valid, as will be discussed later.

The method used to model submerged vegetation included two different components. In one hand, the bathymetry was changed so that the bottom height would be 50% higher than its initial value, meaning no flow would occur through it, and also, the Manning's Number, M, was considered to be lower than the bottom's value, meaning that the roughness and thus the friction on the surface of the vegetation were higher than on the bottom surface without vegetation.

In a simplistic point of view, submerged vegetation was faced as an additional volume in the lake bed, and also with high resistance to the flow, as this additional volume has high rugosity. Figure 4 illustrates the model that was used.

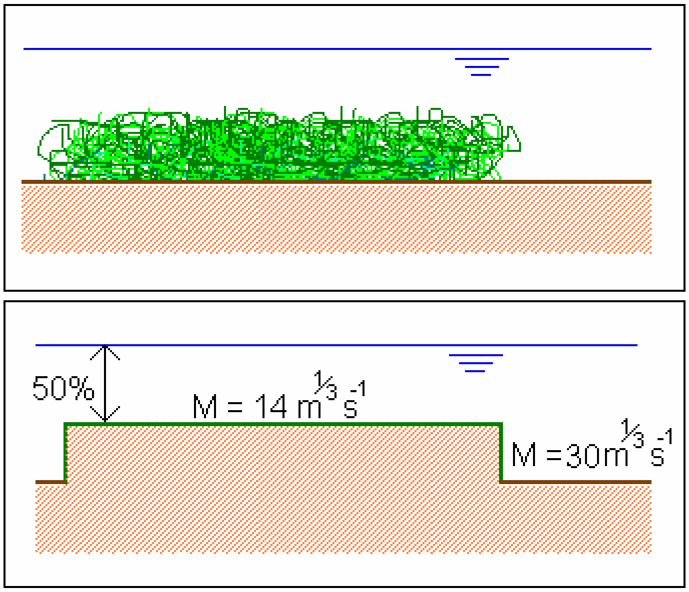

Figure 4. Submerged vegetation model

The other kind of vegetation modelled was the emerged vegetation, which is also very common in most shallow lake environments, such as the reeds seen in Figure 5.

Even though emerged vegetation may also many times be quite dense, it was considered that it would always still allow flow to go trough it. This assumption was made keeping in mind that otherwise the vegetation could simply be replaced by land.

So, in order to simulate the desired behaviour, no change was made to the bottom height in areas with emerged vegetation, but only to the flow resistance, in the form of significantly decreasing the Manning's number, as illustrated in Figure 6.

Figure 5. Reed belts.

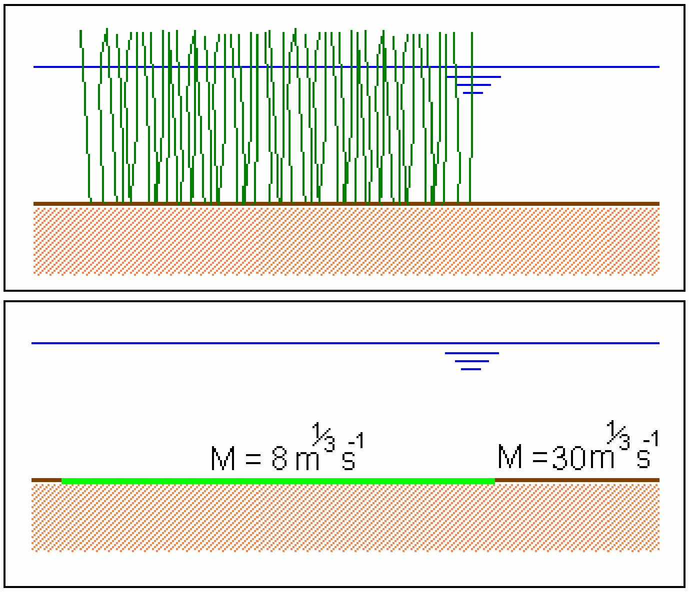

Figure 6. Emerged vegetation model

The choice of values for the Manning's number was based in the author's previous experience working in hydrologic studies, namely for CEHIDRO (Center for Hydro-system Studies of the Instituto Superior Técnico, where the author is a student) in 2004/2005. This work consisted of hydrologic and hydraulic studies in two bridge construction sites, with the final purpose of choosing the protection methods that should be applied to the pillars. The author's work included field trips to the construction sites, and consisted of both flow level and current speed predictions using empiric models and statistic treatments for flood flows, and a numeric cross-section model developed for the purpose, where vegetation was also included by means of altering the Manning Number, to predict the current speeds. This work was ordered to CEHIDRO by Armando Rito S.A., the private company responsible for the construction of both bridges, and resulted in two technical reports, namelly "Ponte sobre o rio Corgo no sub-lanço D1, Fortuno/Falperra, integrado no IP3 – Condicionantes hidrológicos e hidráulicos" and "Viaduto de Vila Pouca de Aguiar no sub-lanço E1, Falperra/Pedras Salgadas, integrado no IP3 – Condicionantes hidrológicos e hidráulicos".

Having said this, for the first scenario, the one of submerged vegetation, the value for the Manning's M was assumed to be $14m^{1/3}s^{-1}$, and in the second scenario, for the emerged vegetation, or reed belts, the value was chosen as $8m^{1/3}s^{-1}$. The value adopted for the unvegetation areas of the models was $30m^{1/3}s^{-1}$, as can be seen in the figures illustrating the models.

Although changing these values would necessarily affect the final outcome of the modelling, they were kept constant throughout the simulations, as the goal was to test the validity of the modelling techniques, and not to focus on the values used for vegetation themselves. This means that the only concern behind the values chosen was to make them reliable enough, and then study different surroundings and see if the effects obtained were plausible.

Once the methods to simulate vegetation were laid out, several case scenarios were tested.

To begin with, a bathymetry grid was created to use in MIKE 21, with the single purpose to run the first simulations. Such grid consisted of a square lake, with 100m x 100m and a 2 meter grid. All initial runs made in this square lake model were done using a constant wind speed of 10 m/s.

Two different runs were done in this model, to further use as a reference. Both of them were done under the exact same conditions, except for the wind direction. One of them was done considering wind from East, and the other one was done with wind from South.

Being a square lake there should be no need to run these to simulations, as one could be obtained from the other simply by rotating the values 90 degrees. They were still done, however, for easier comparison with other runs, as East and South were always the directions used in the runs.

The reason to chose these to distinct wind directions was related with the fact that Lake Krankesjön was used for field measurements, and the wind directions that are felt in the lake area vary a lot along time (see table 1). This would then make it easier to get a better perspective of how the results could change with different wind conditions, and still be able to relate the results given by the model and the measurements made in the lake.

Table 1 – Dominant wind direction. Stensoffa Ecological Station

Year	Month	Dominant Wind Direction
2004	3	E
	4	E
	5	E
	6	SSW
	7	SW
	8	E
	9	SW
	10	E
	11	SW
	12	SW
2005	1	SSW
	2	N
	3	ENE
	4	ENE
	5	S
	6	WNW

After these two initial runs, four more were done, also in a purely theoretical scenario. The same square lake was used, but this time considering both vegetation simulations being studied, and both considering that half the lake was vegetated, and the other half was not. Each of the two vegetation models was run with both east and south wind, thus resulting in four simulations. Figure 7 shows a schematic perspective of what was done.

The purpose of these simulations was to visualize the different impact the two different types of vegetation would have on the hydrodynamics, comparing with the initial two runs.

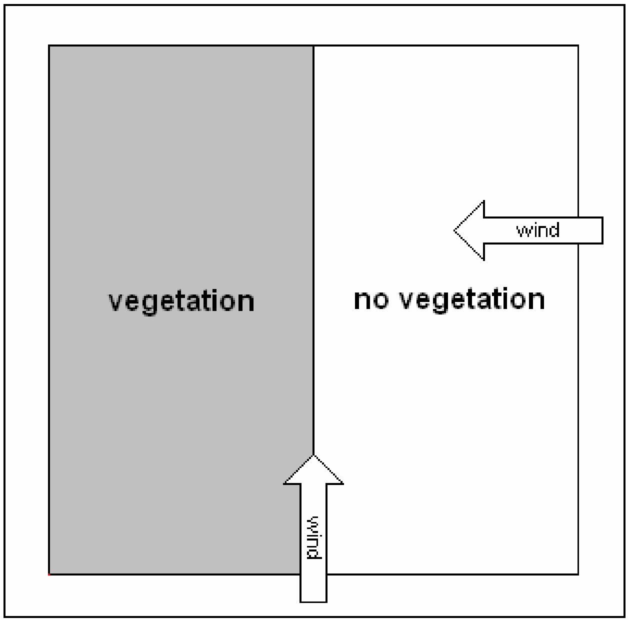

Figure 7. Vegetated square lake models.

Once these first runs were made, all further runs were done using the bathymetry data of Lake Krankesjön. The bathymetry was created using the MIKE21 bathymetry editor, using Figure 8 as a background reference. The bathymetry file was created as a rectangle with 2500m x 3000m and a 10m grid spacing.

The first runs using the real lake bathymetry were done considering no vegetation would be present. This was done in one hand to compare with the vegetated situation, and therefore extract information about the influence of vegetation, but also due to the fact that vegetation can dramatically change along the year, and it would therefore also be interesting to run different simulations with different states of vegetation growth, including this case, of no vegetation.

All simulations made to the real bathymetry included four different runs. Each of the two wind directions described were tested, East and South, and both of them using constant wind speeds of 5 and 10 m/s.

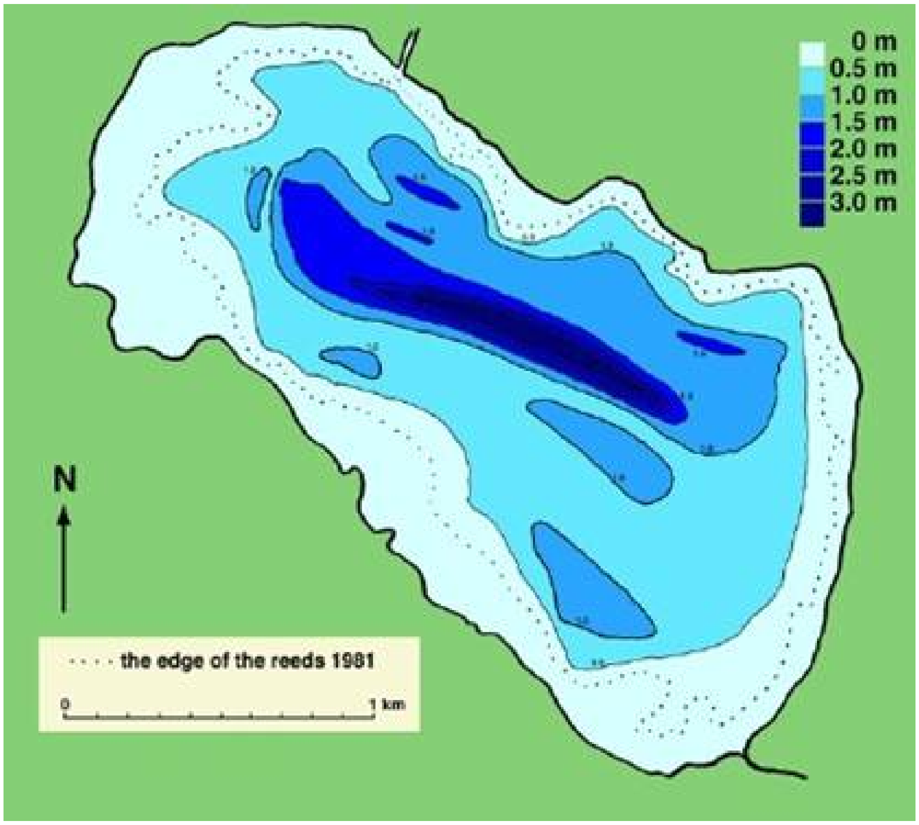

Figure 8. Bathymetry background for Krankesjön. (Lake Krankesjön – Limnology at the University of Lund – Link 7)

These runs were made in i) the real lake with no vegetation, as just stated; ii) the real lake with approximately 20% vegetation cover, using a reading from 1989 (see Figure 9), both considering only submerged vegetation and mixed vegetation, and finally, iii) using the vegetation cover measured in October 2004, were it covers most of the lake, as shown in Figure 10.

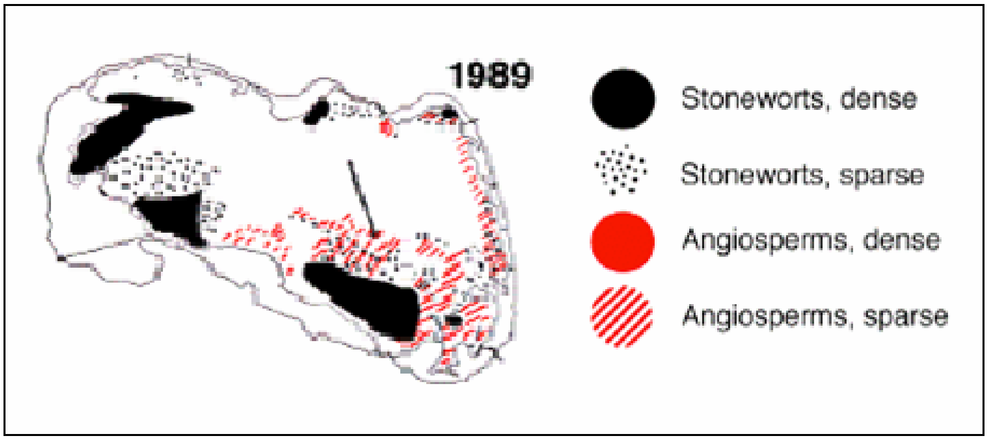

Figure 9. Vegetation cover in Lake Krankesjön, 1989. (Link 6)

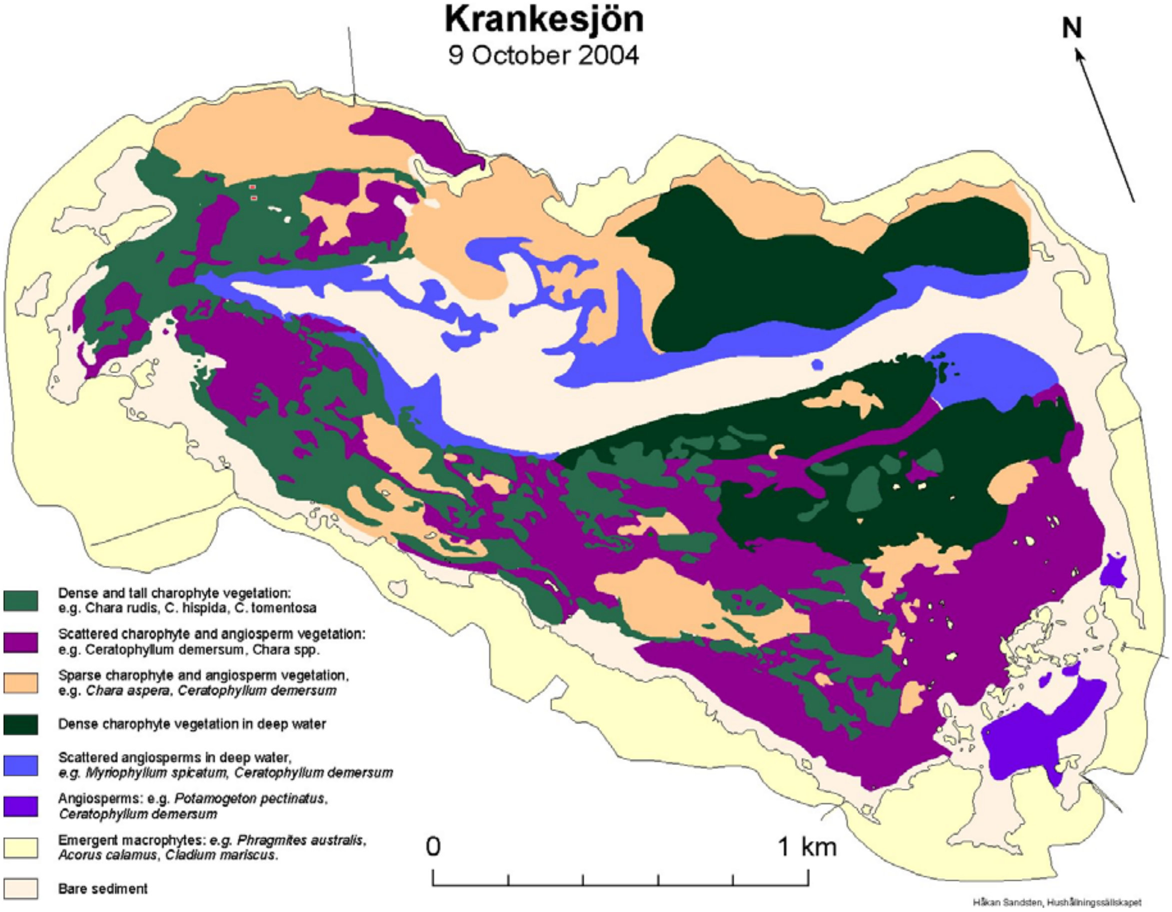

Figure 10. Vegetation cover in Lake Krankesjön, October 2004. (Håkan Sandsten, Hushållningssällskapet)

For better understanding of what was made all runs are schematized in the table 2.

Table 2 – Case scenarios summary

Reference	Bathymetry	Vegetation	Wind Conditions
1a	Square lake	None	East, 10 m/s
1b	Square lake	None	South, 10 m/s
2a	Square lake	Submerged, 50%	East, 10 m/s
2b	Square lake	Submerged, 50%	South, 10 m/s
2c	Square lake	Emerged, 50%	East, 10 m/s
2d	Square lake	Emerged, 50%	South, 10 m/s
3a	Krankesjön	None	East, 5 m/s
3b	Krankesjön	None	East, 10 m/s
3c	Krankesjön	None	South, 5 m/s
3d	Krankesjön	None	South, 10 m/s

Table 2 – Case scenarios summary (continuation)

Reference	Bathymetry	Vegetation	Wind Conditions
4a	Krankesjön	Submerged, 1989	East, 5 m/s
4b	Krankesjön	Submerged, 1989	East, 10 m/s
4c	Krankesjön	Submerged, 1989	South, 5 m/s
4d	Krankesjön	Submerged, 1989	South, 10 m/s
5a	Krankesjön	Mixed, 1989	East, 5 m/s
5b	Krankesjön	Mixed, 1989	East, 10 m/s
5c	Krankesjön	Mixed, 1989	South, 5 m/s
5d	Krankesjön	Mixed, 1989	South, 10 m/s
6a	Krankesjön	Mixed, 2004	East, 5 m/s
6b	Krankesjön	Mixed, 2004	East, 10 m/s
6c	Krankesjön	Mixed, 2004	South, 5 m/s
6d	Krankesjön	Mixed, 2004	South, 10 m/s

4 RESULTS

The first results to be collected were the ones extracted from the MIKE 21 modelling. Although it is possible to extract different kinds of information from the MIKE 21 hydrodynamic module, the most relevant results to this work were the water levels and the current speeds, since those are the values that can be related to the values obtained in the field measurements.

Since the models are two-dimensional, the results are better displayed in a colour-scaled overview, although it is possible to extract the numeric values for each grid node. The interpretation of the results is strongly based on a visual analysis, which should be done considering also the values in each scale, which are not always the same.

As explained, the results displayed here consist of water level diagrams, current speed diagrams, but also in some cases, and in order to better understand the scenarios, diagrams containing the Manning values used. The order of the display will be the water levels for each group of scenarios, mostly to understand the bathymetry, the Manning values, if necessary, and then the current speed diagrams for each case, which are the most important results. Since it was also important to evaluate the changes in preferential paths, all the current speed diagrams have the speed vectors drawn once in every 25 nodes, making the reading of the diagrams easier.
In order to better understand the results, a brief description of each scenario is also included.

The order of greatness of the speed values obtained was always of centimetres per second, and these were influenced a lot by the wind speed, just as expected. Typically the maximum current speeds for 5m/s wind were 5 to 7cm/s, while with 10m/s the these values ranged from 10 to 15m/s. The speed distributions changed a lot in the different scenarios, mostly by changing the wind conditions, but also by introducing the vegetation. The current speed distributions were also quite variable, influenced once again both by the presence of vegetation and wind conditions.

All the diagrams of the results obtained are shown as follows.

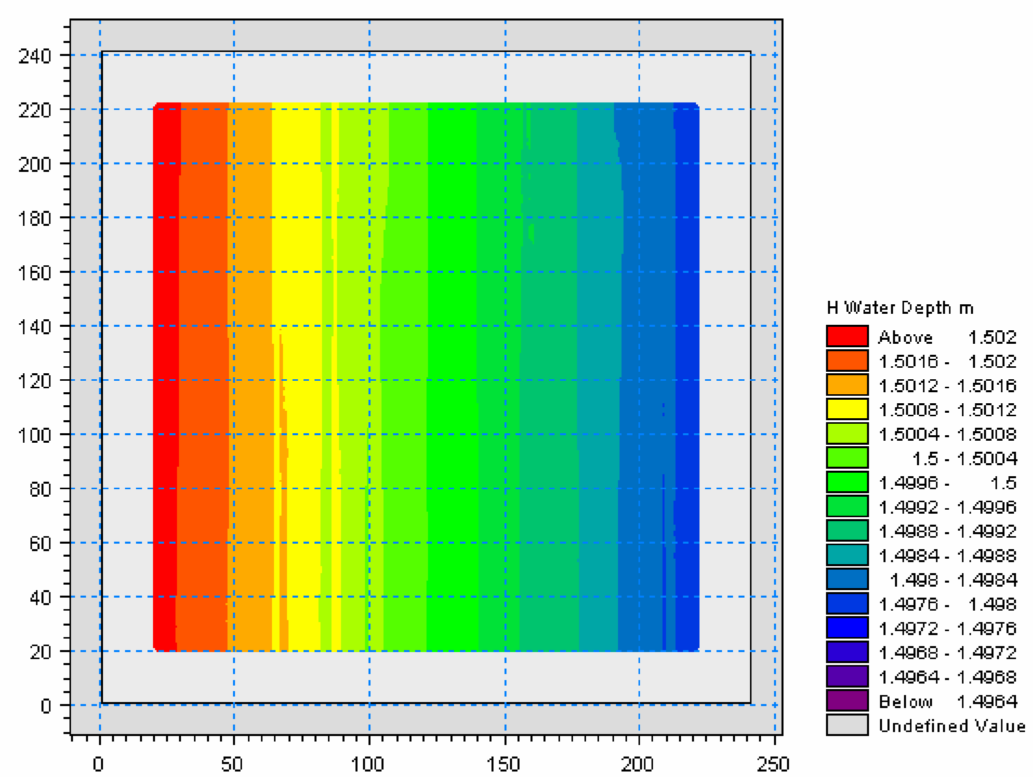

Figure 11. 1a – Square lake; No vegetation; Wind: east, 10m/s. Water levels

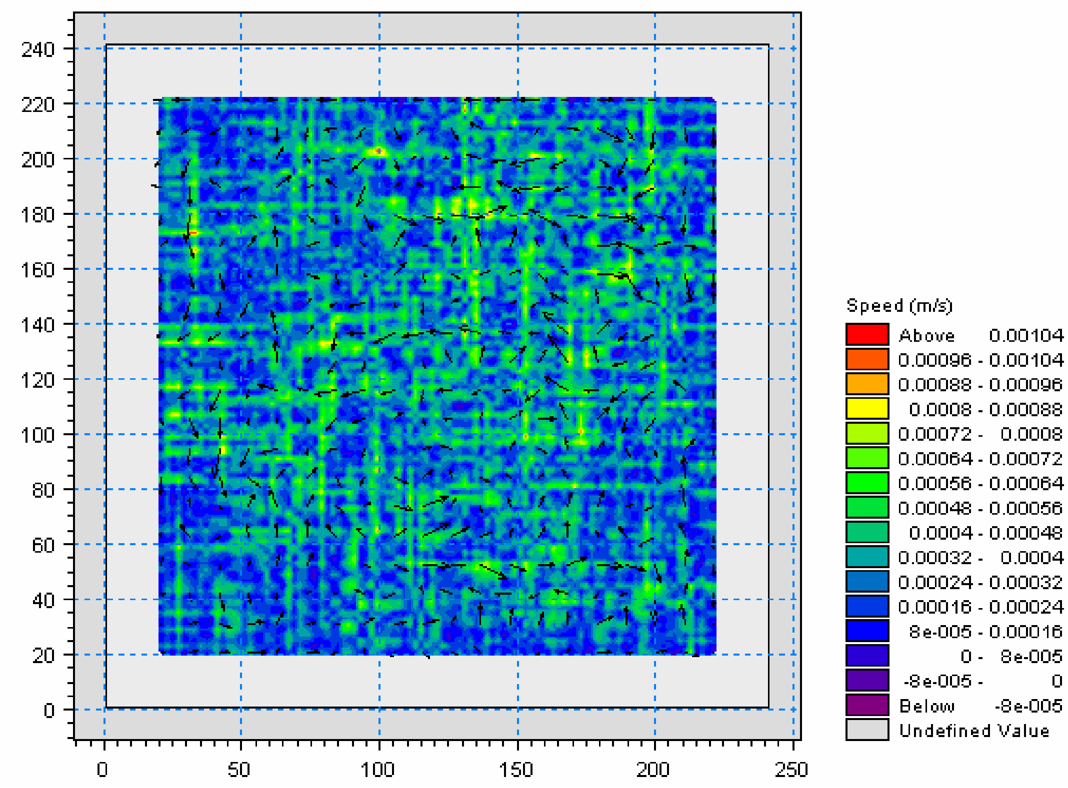

Figure 12. 1a – Square lake; No vegetation; Wind: east, 10m/s. Current speed

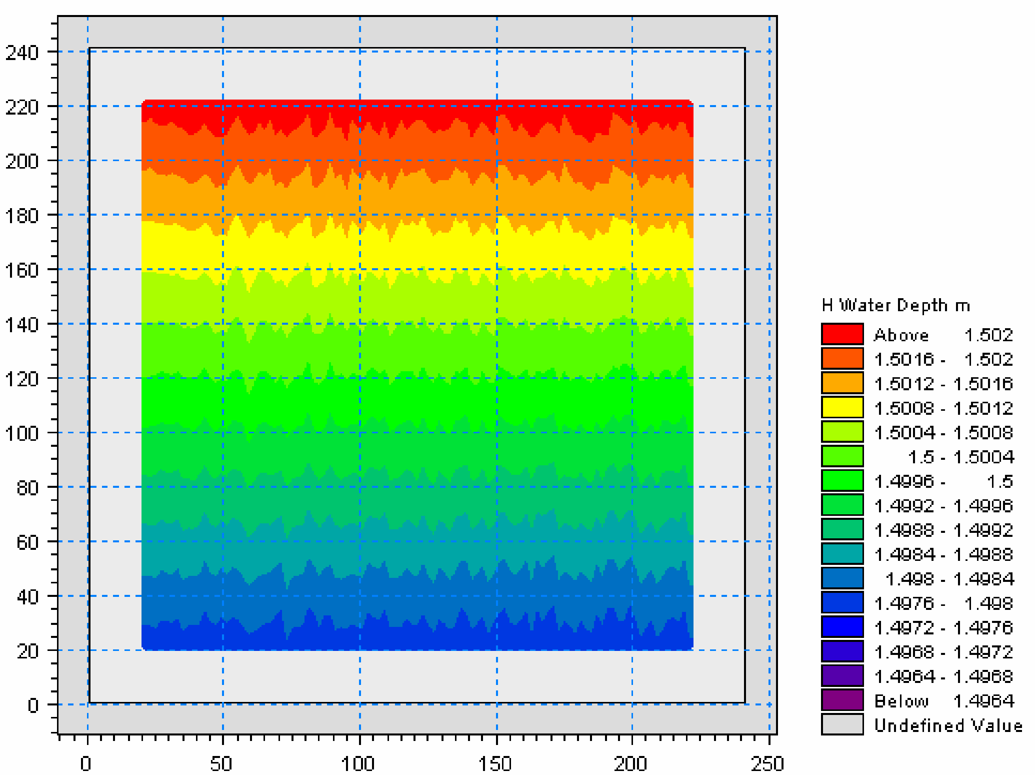

Figure 13. 1b – Square lake; No vegetation; Wind: south, 10m/s. Water levels

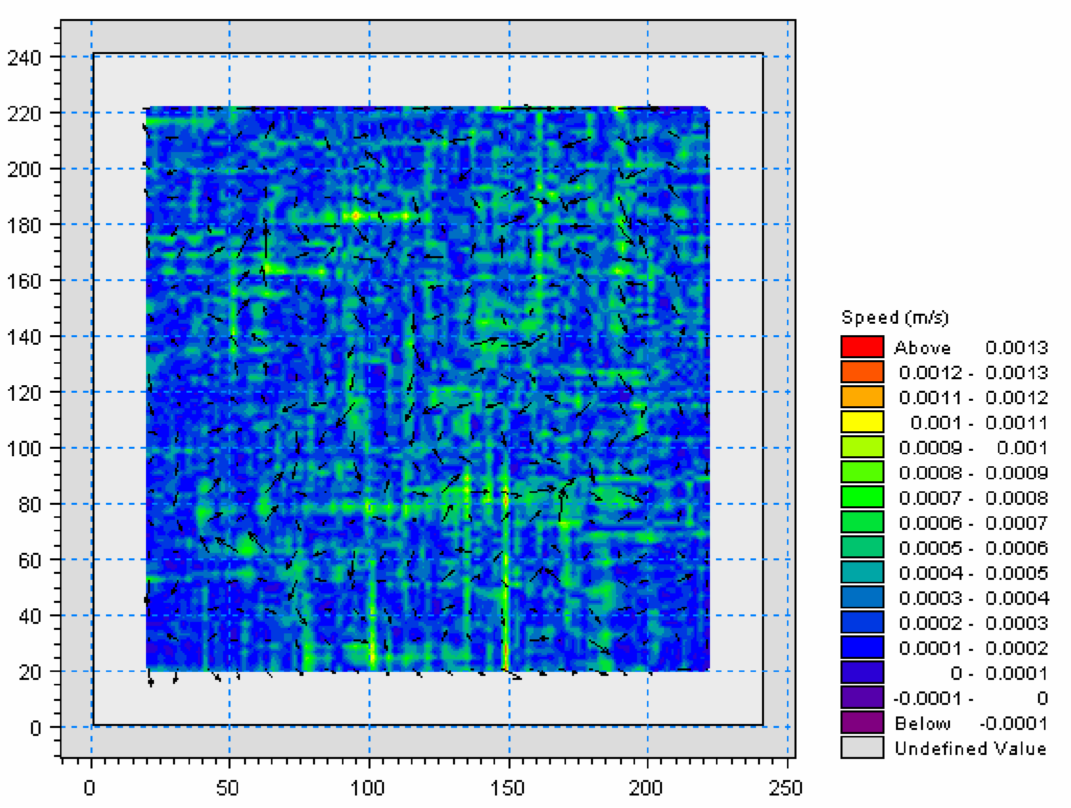

Figure 14. 1b – Square lake; No vegetation; Wind: south, 10m/s. Current speed

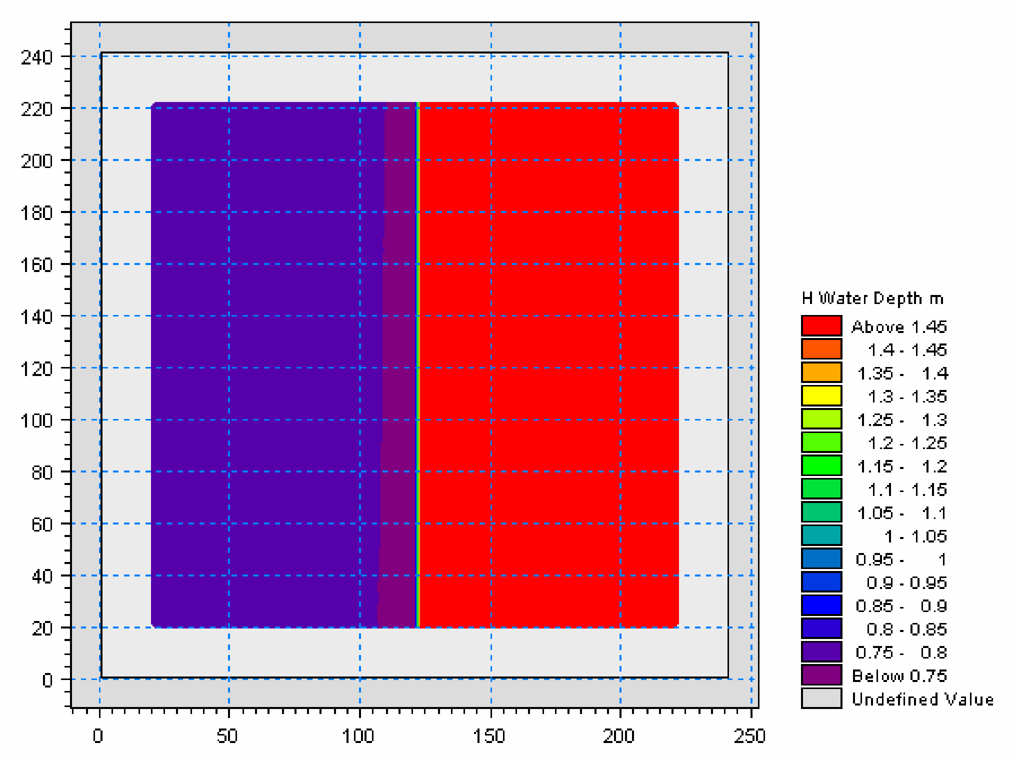

Figure 15. 2a – Square lake; 50% submerged vegetation; Wind: east, 10m/s. Water levels

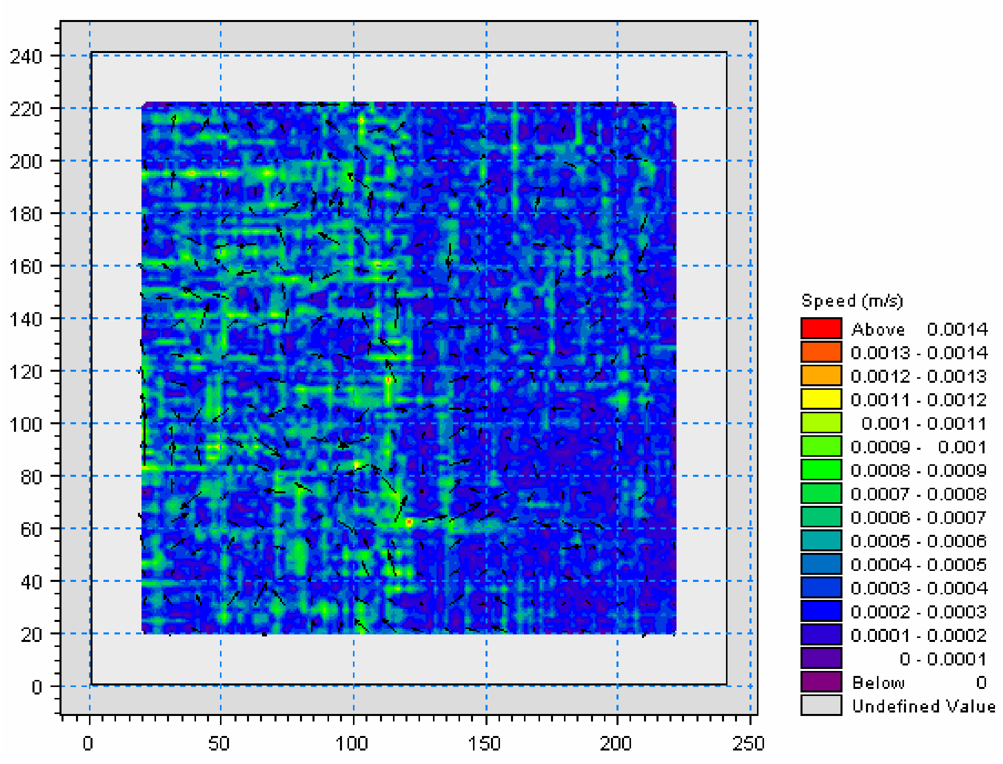

Figure 16. 2a – Square lake; 50% submerged vegetation; Wind: east, 10m/s. Current speed

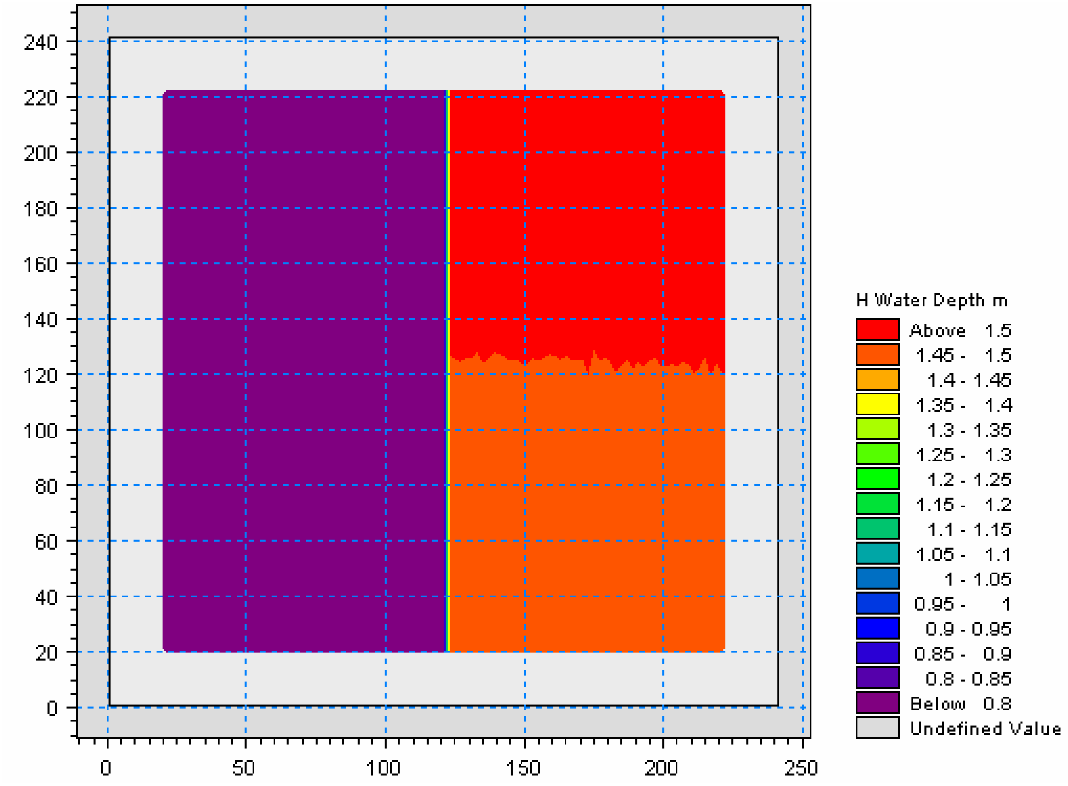

Figure 17. 2b – Square lake; 50% submerged vegetation; Wind: south, 10m/s. Water levels

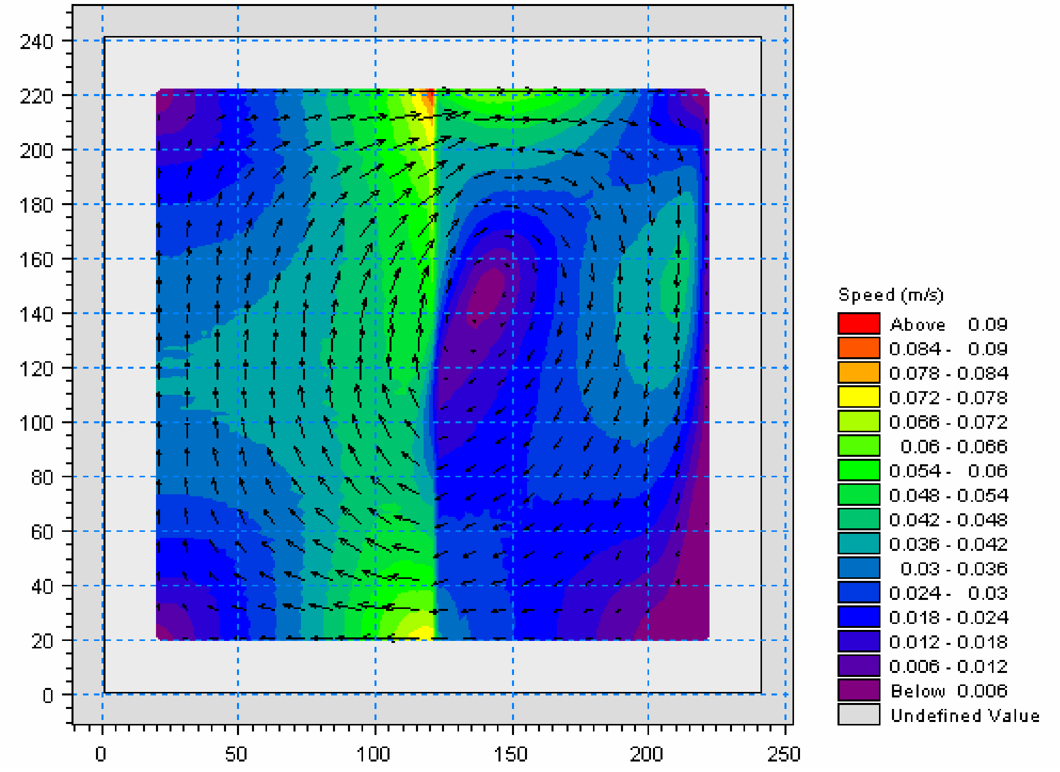

Figure 18. 2b – Square lake; 50% submerged vegetation; Wind: south, 10m/s. Current speed

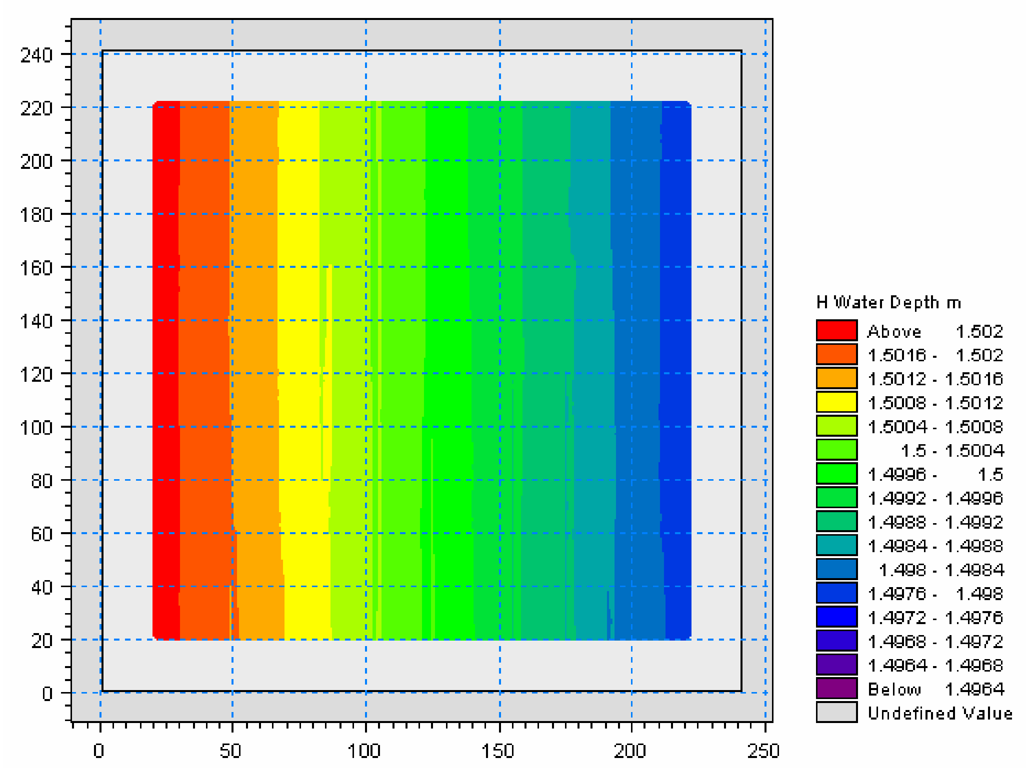

Figure 19. 2c – Square lake; 50% emerged vegetation; Wind: east, 10m/s. Water levels

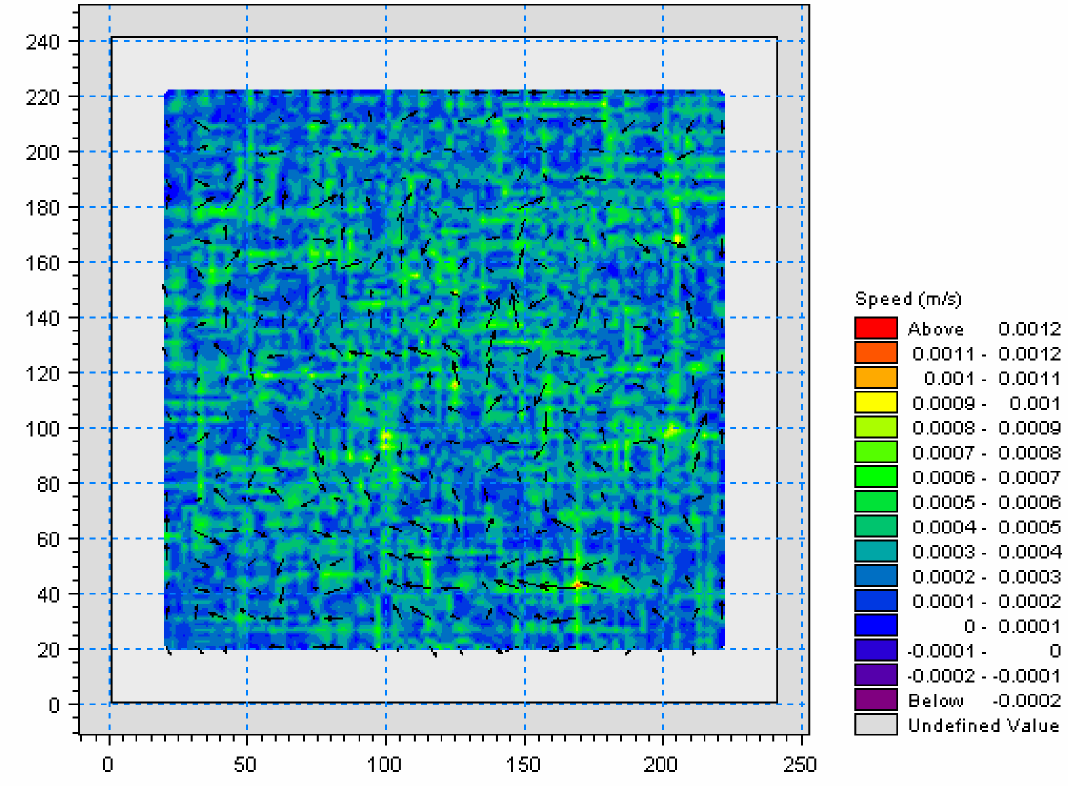

Figure 20. 2c – Square lake; 50% emerged vegetation; Wind: east, 10m/s. Current speed

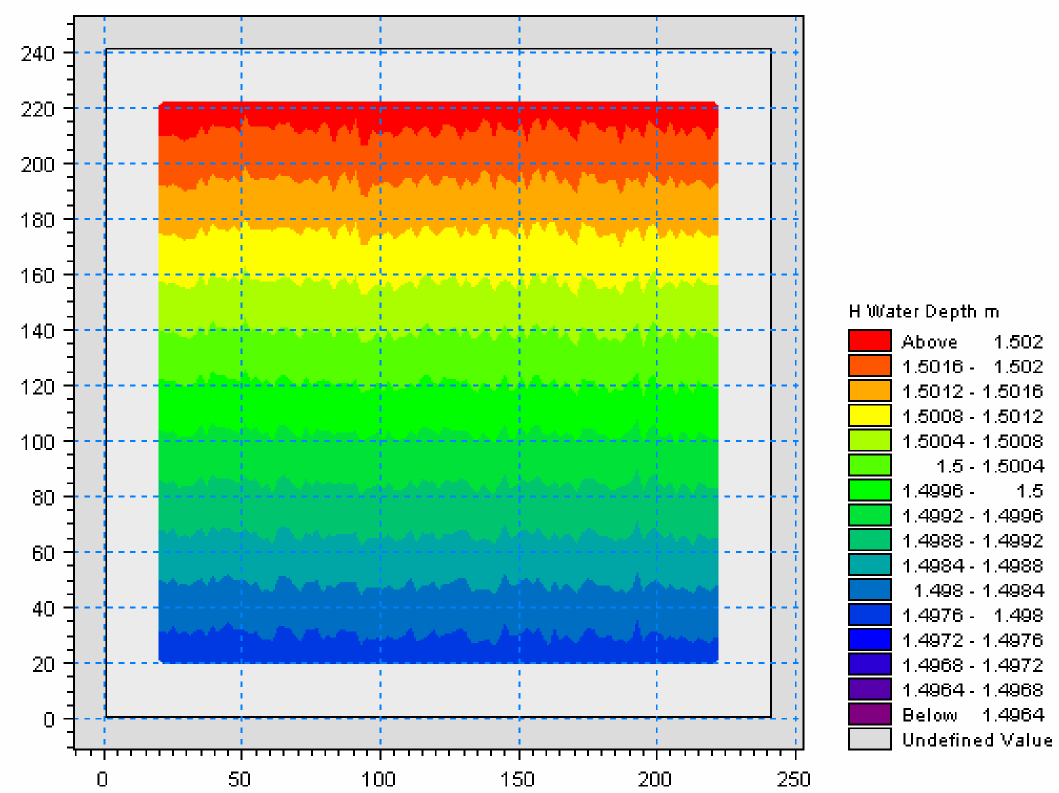

Figure 21. 2d – Square lake; 50% emerged vegetation; Wind: south, 10m/s. Water levels

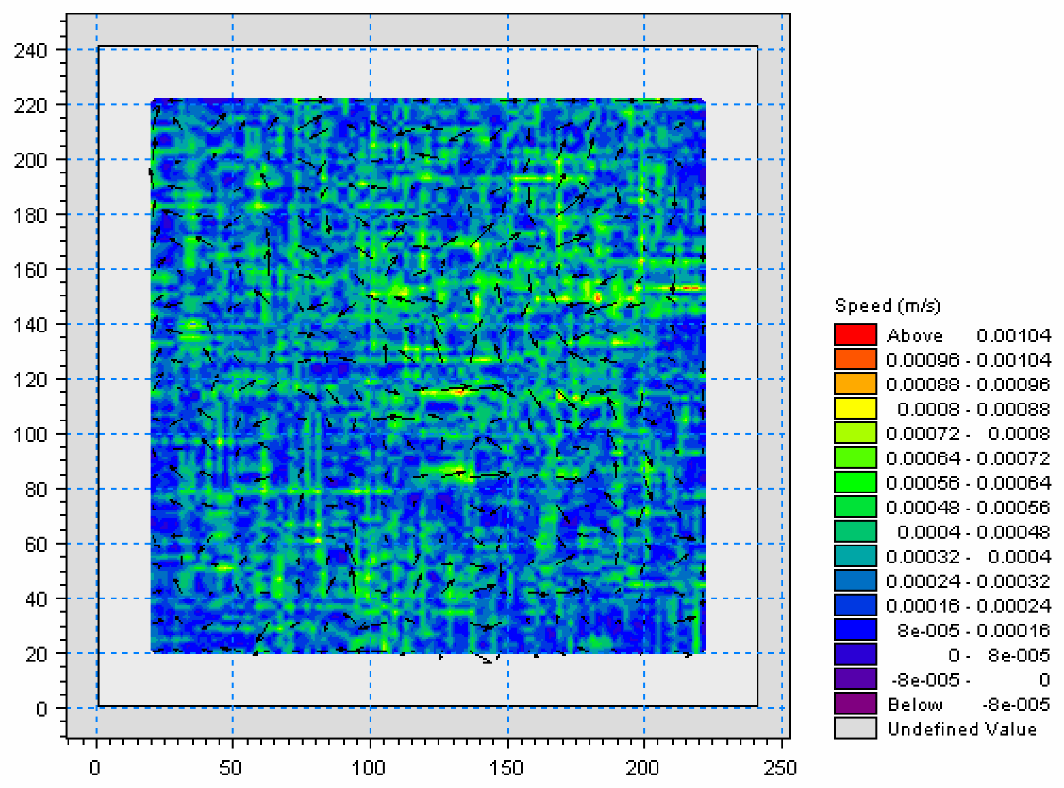

Figure 22. 2d – Square lake; 50% emerged vegetation; Wind: south, 10m/s. Current speed

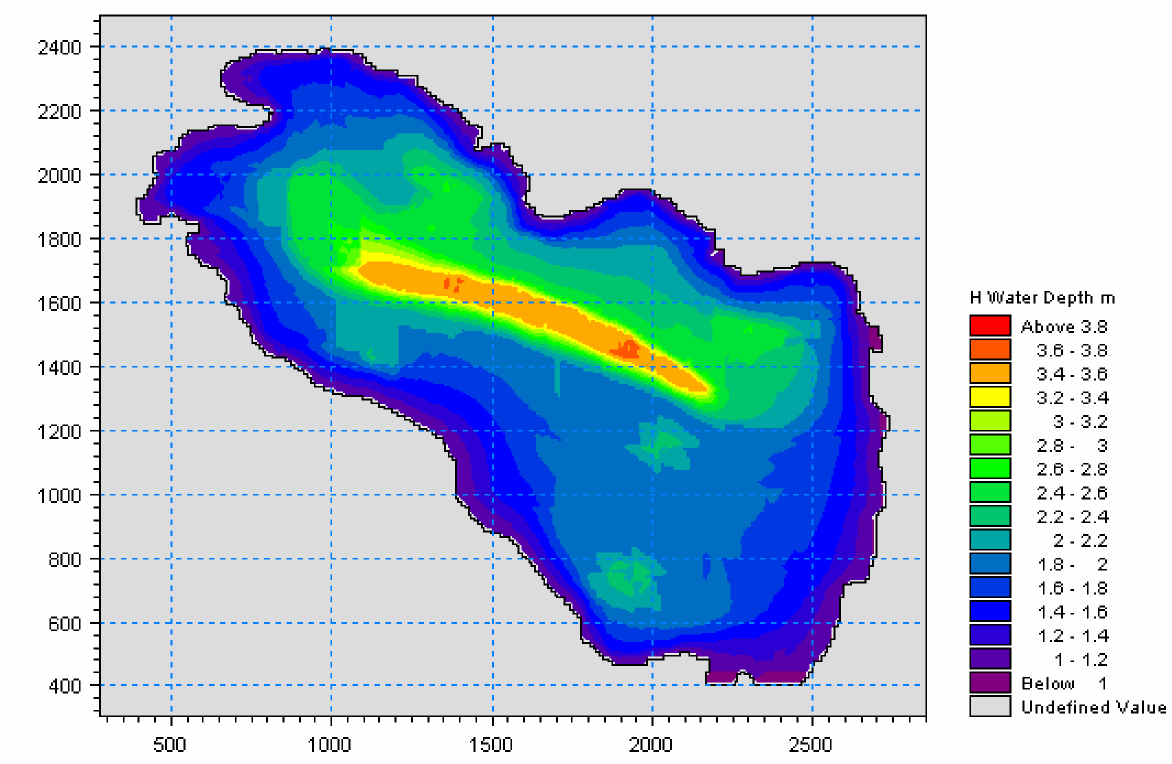

Figure 23. 3a to 3d – Krankesjön; no vegetation. Water levels

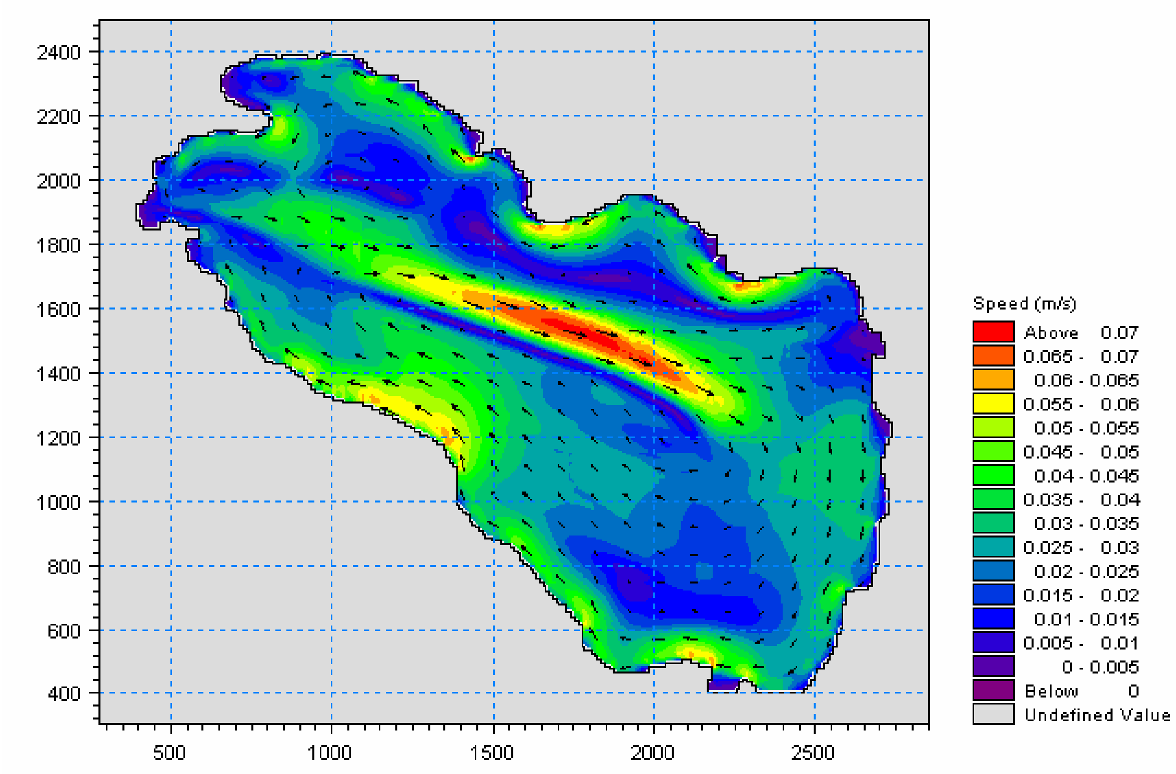

Figure 24. 3a – Krankesjön; no vegetation; Wind: east, 5m/s. Current speed

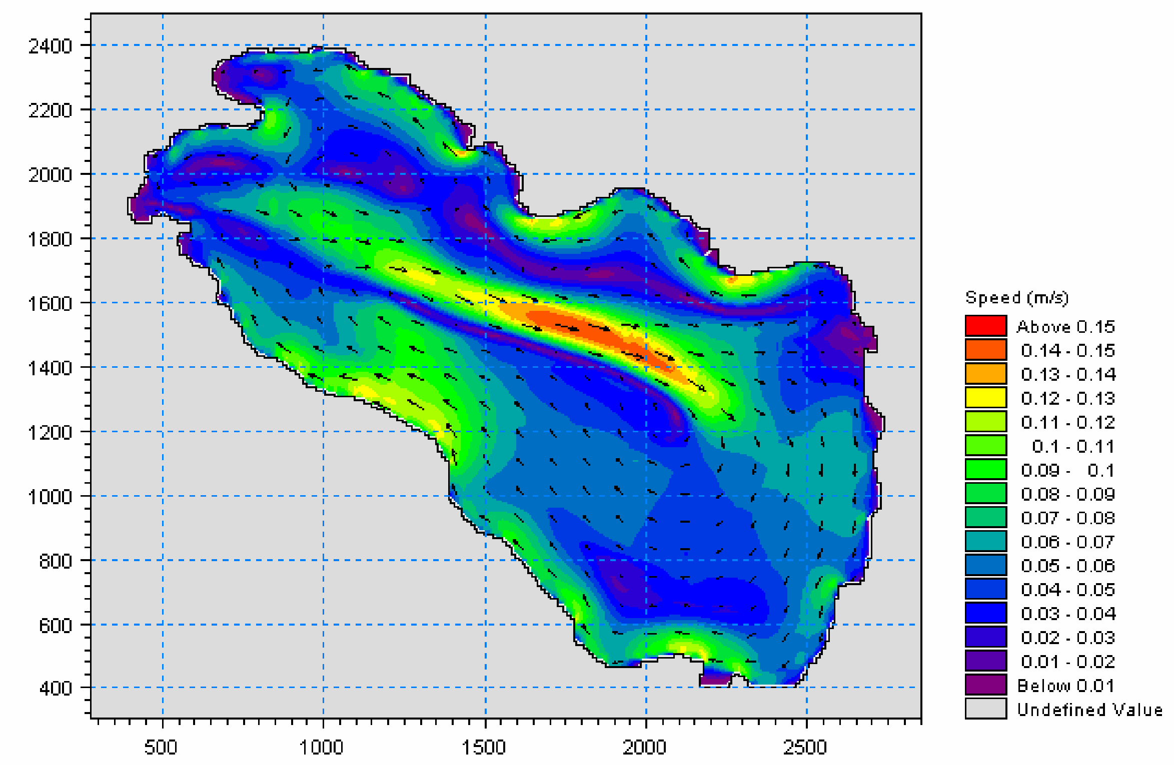

Figure 25. 3b – Krankesjön; no vegetation; Wind: east, 10m/s. Current speed

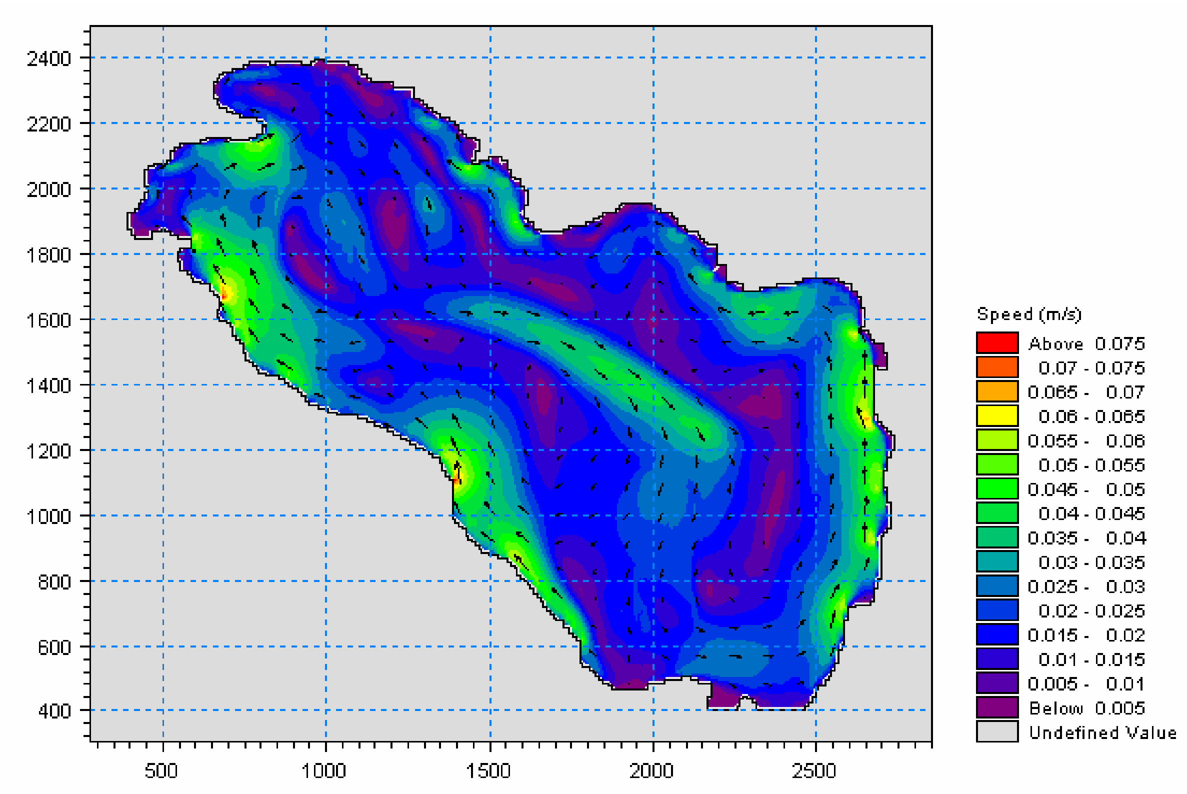

Figure 26. 3c – Krankesjön; no vegetation; Wind: south, 5m/s. Current speed

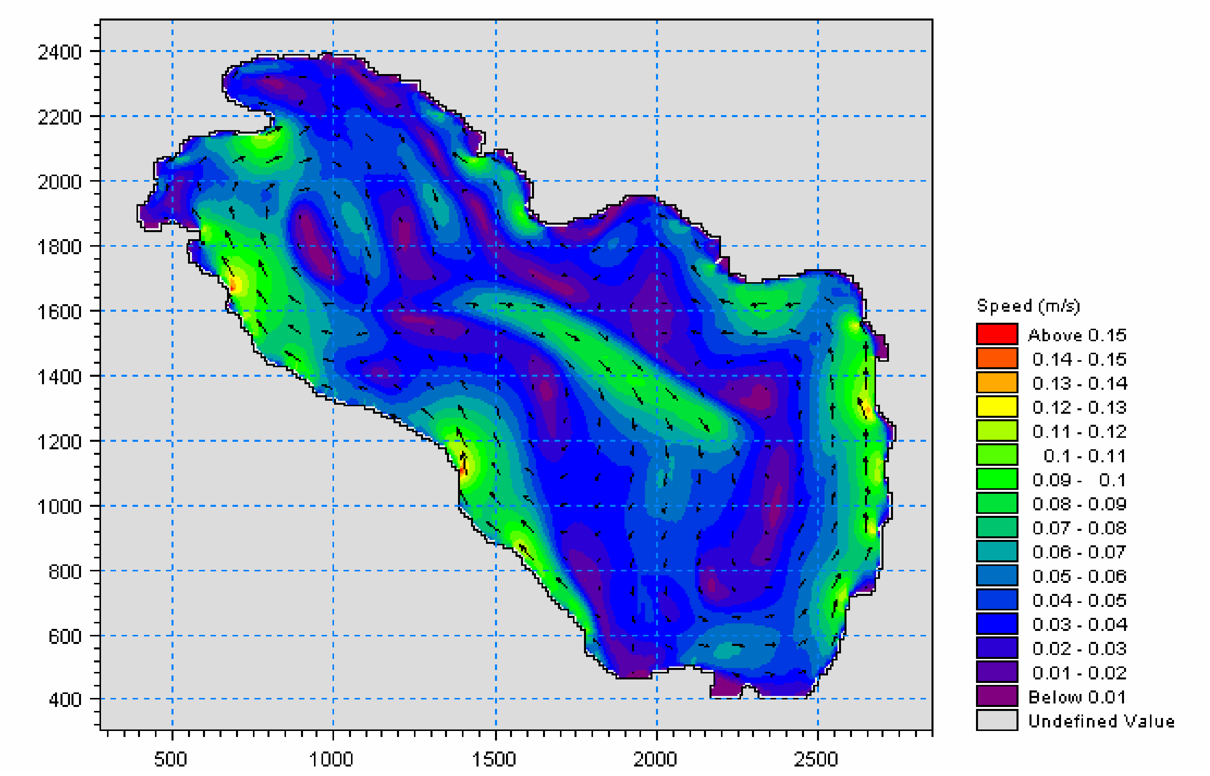

Figure 27. 3d – Krankesjön; no vegetation; Wind: south, 10m/s. Current speed

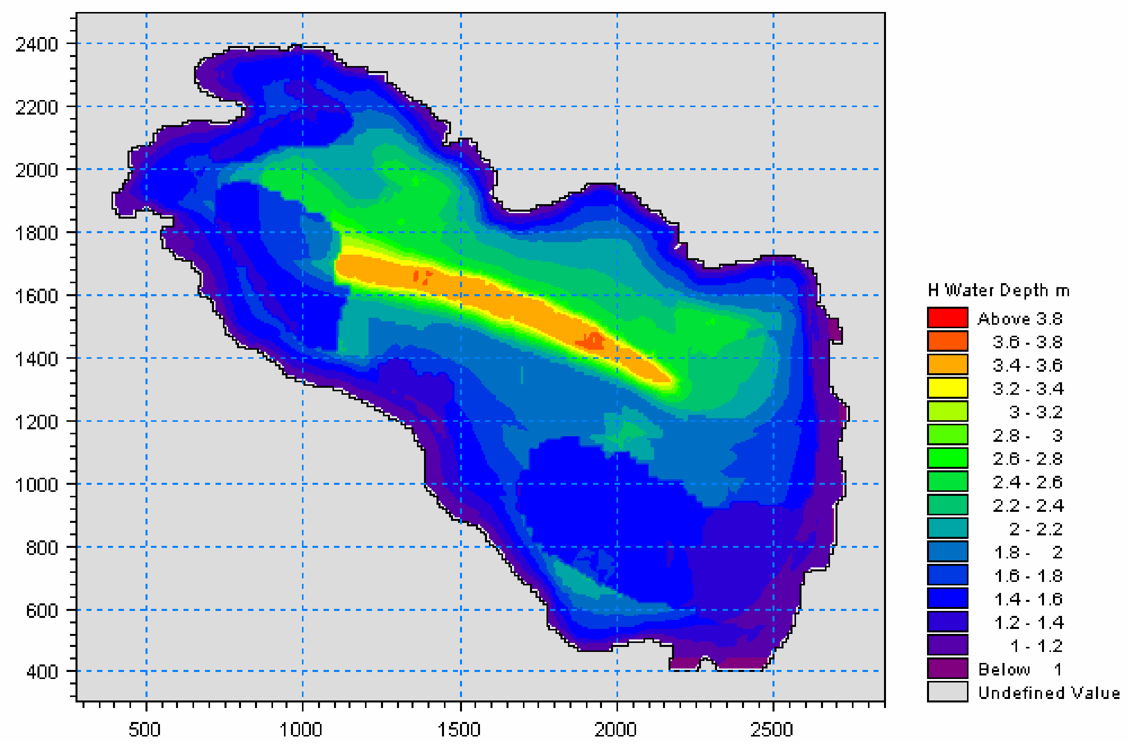

Figure 28. 4a to 5d – Krankesjön; 1989 vegetation. Water levels

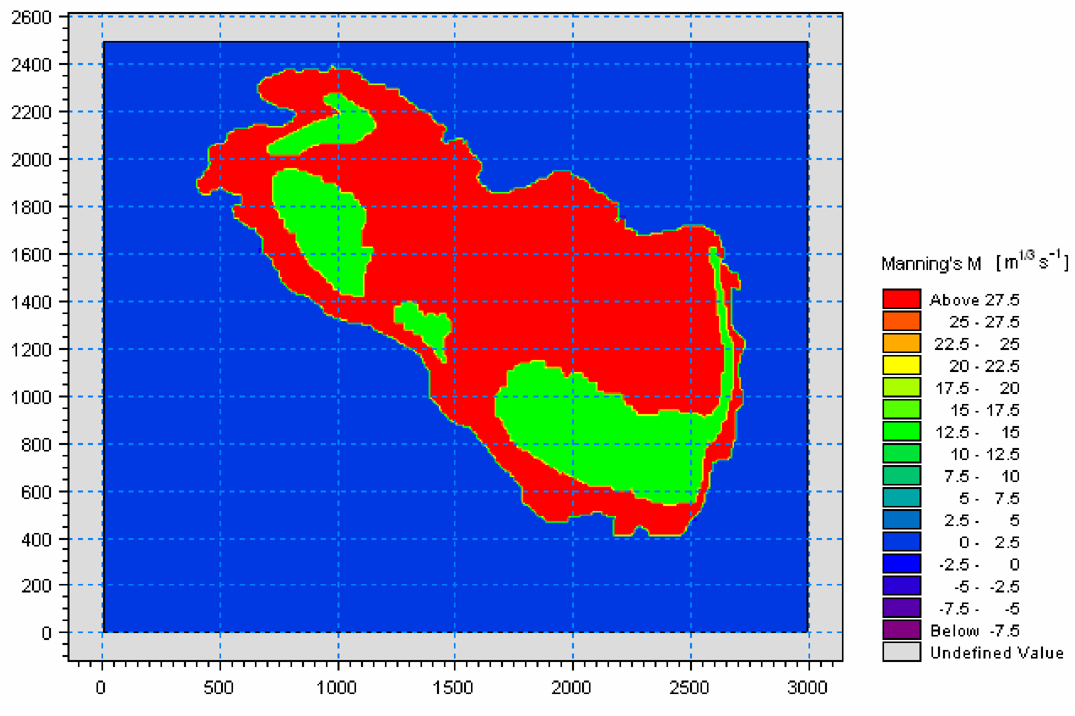

Figure 29. 4a to 4d – Krankesjön; 1989 submerged vegetation. Manning values.

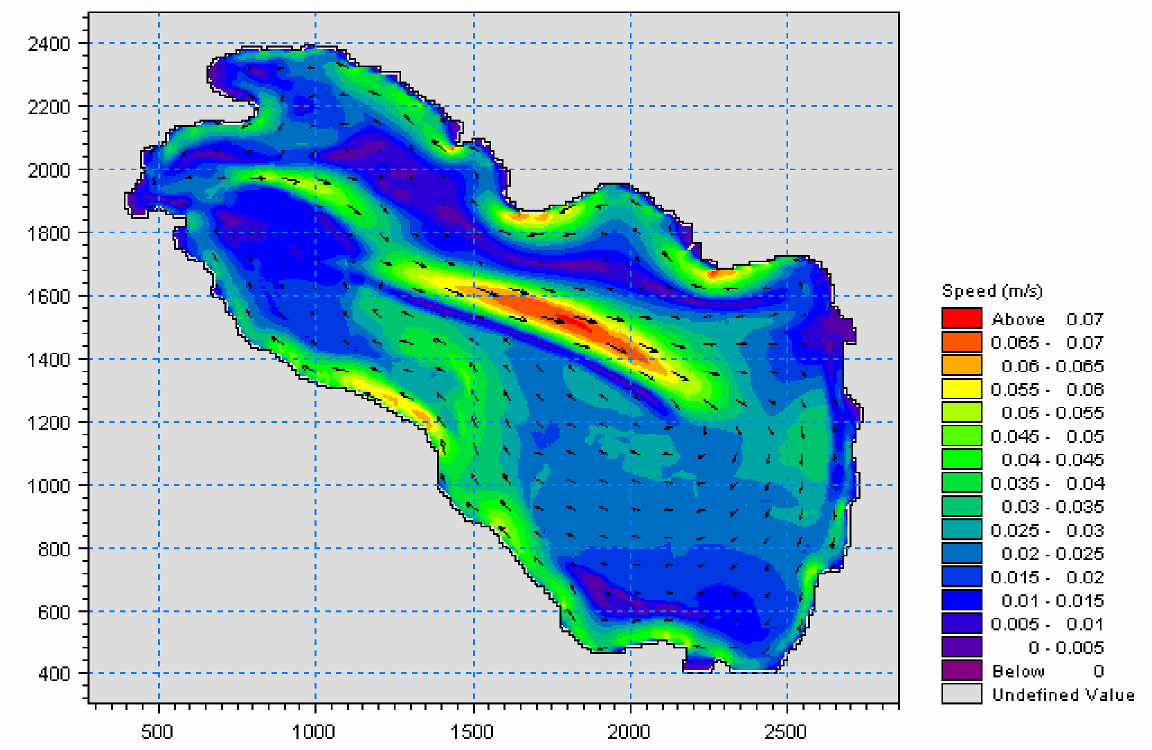

Figure 30. 4a – Krankesjön; 1989 submerged vegetation; Wind east, 5m/s. Current speed

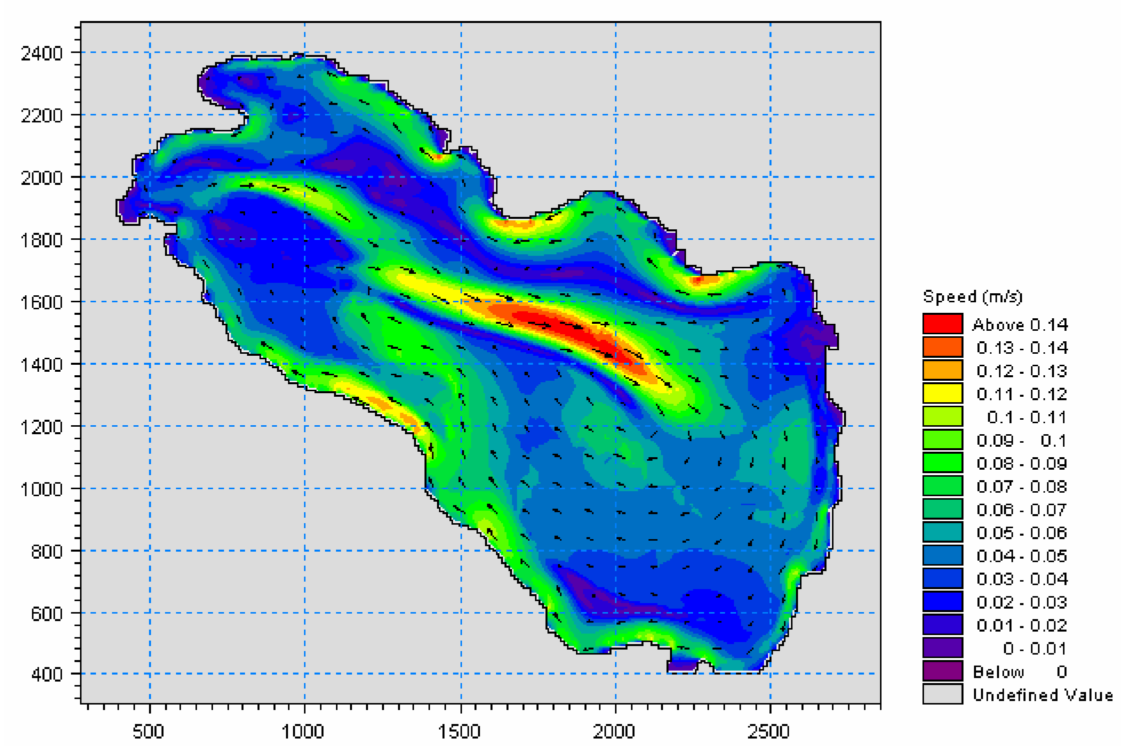

Figure 31. 4b – Krankesjön; 1989 submerged vegetation; Wind east, 10m/s. Current speed

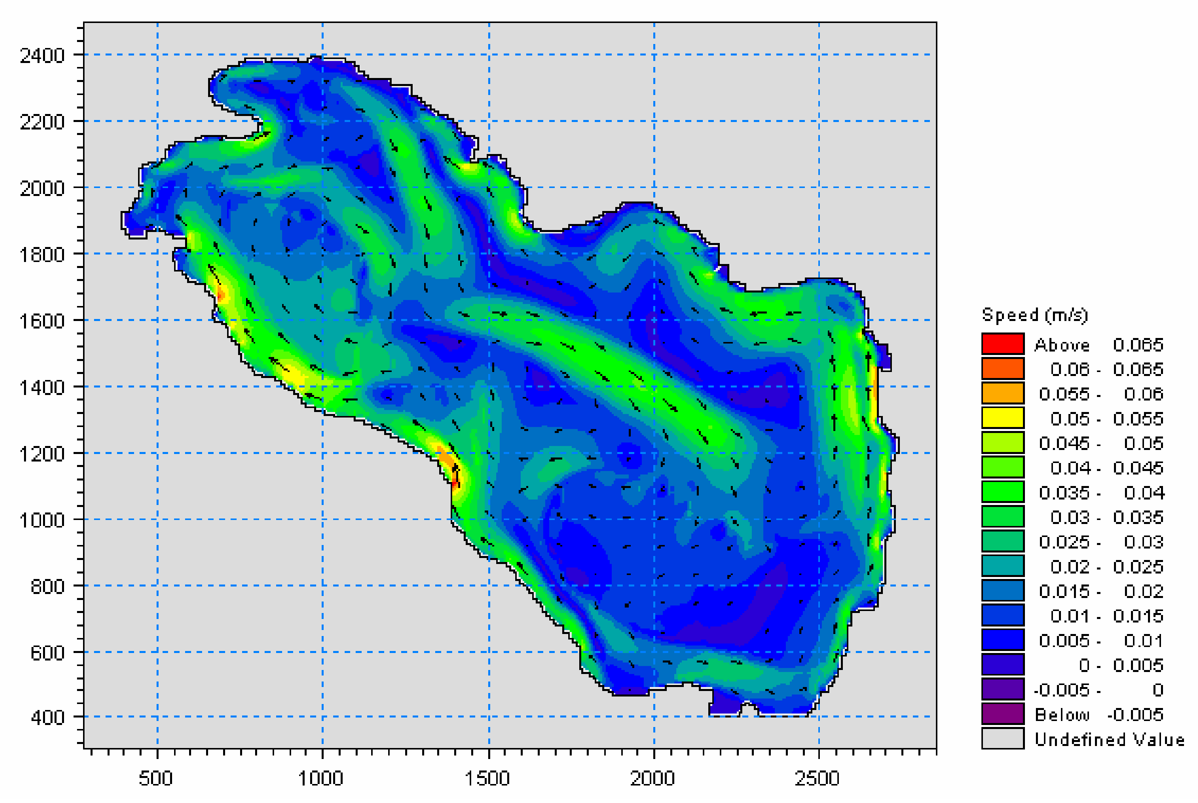

Figure 32. 4c – Krankesjön; 1989 submerged vegetation; Wind south, 5m/s. Current speed

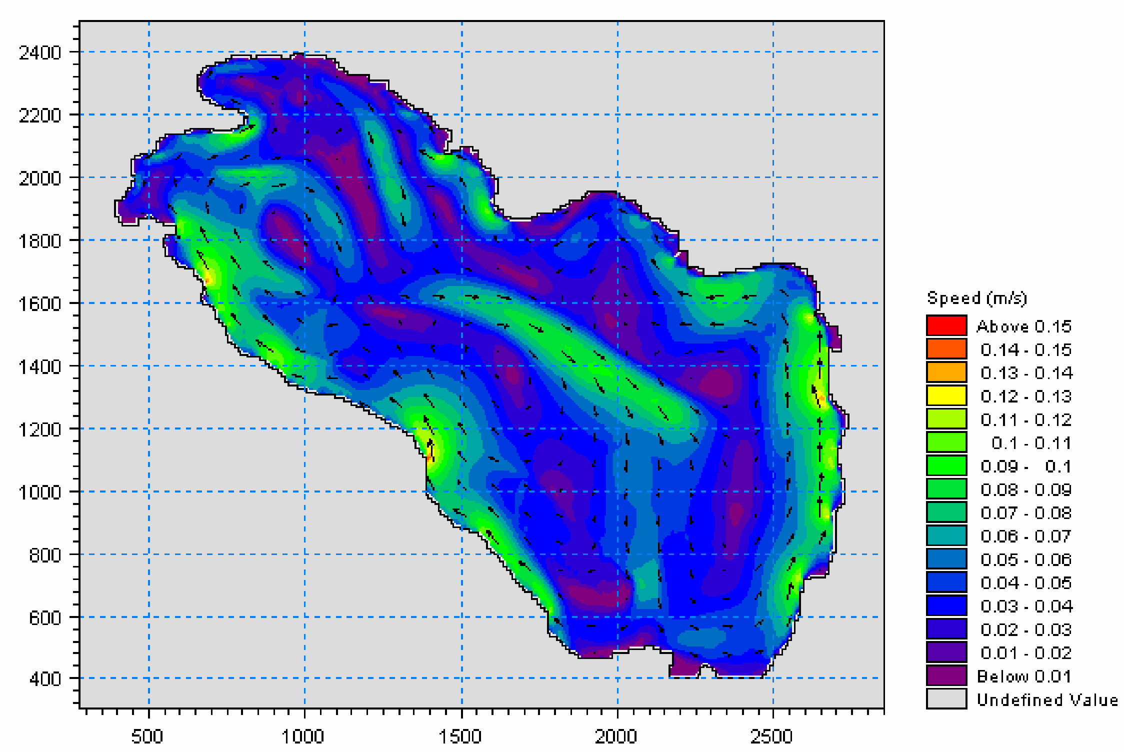

Figure 33. 4d – Krankesjön; 1989 submerged vegetation; Wind south, 10m/s. Current speed

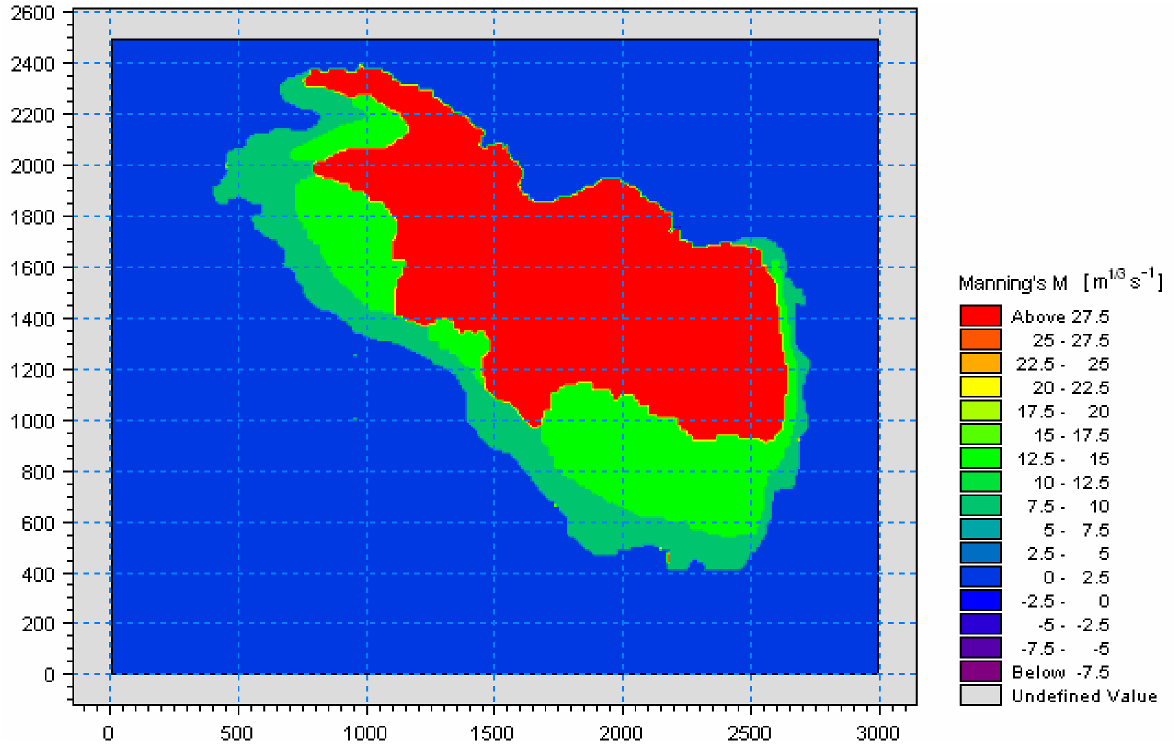

Figure 34. 5a to 5d – Krankesjön; 1989 vegetation. Manning values

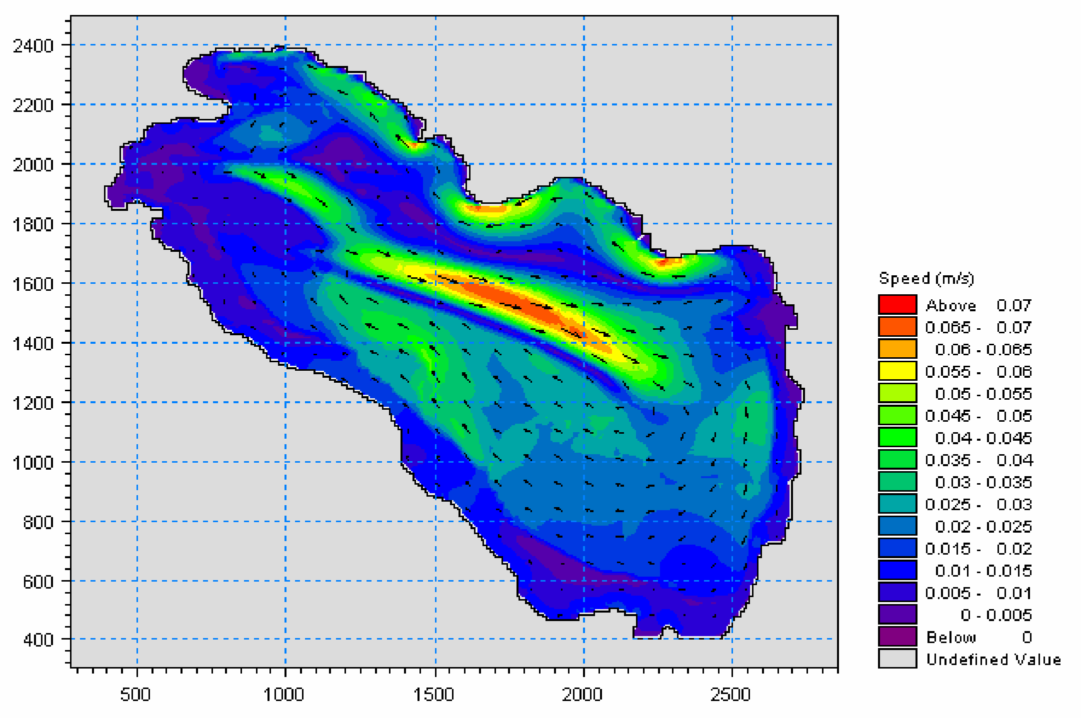

Figure 35. 5a – Krankesjöm; 1989 vegetation; Wind: east, 5m/s. Current speed

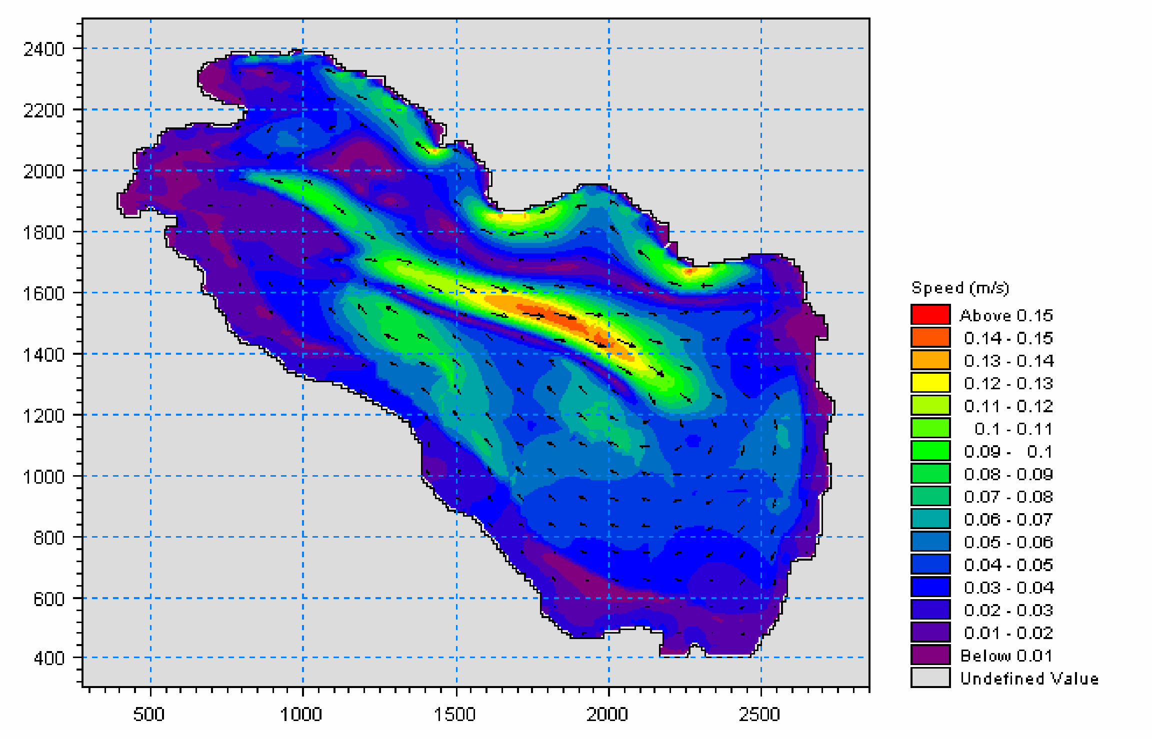

Figure 36. 5b – Krankesjöm; 1989 vegetation; Wind: east, 10m/s. Current speed

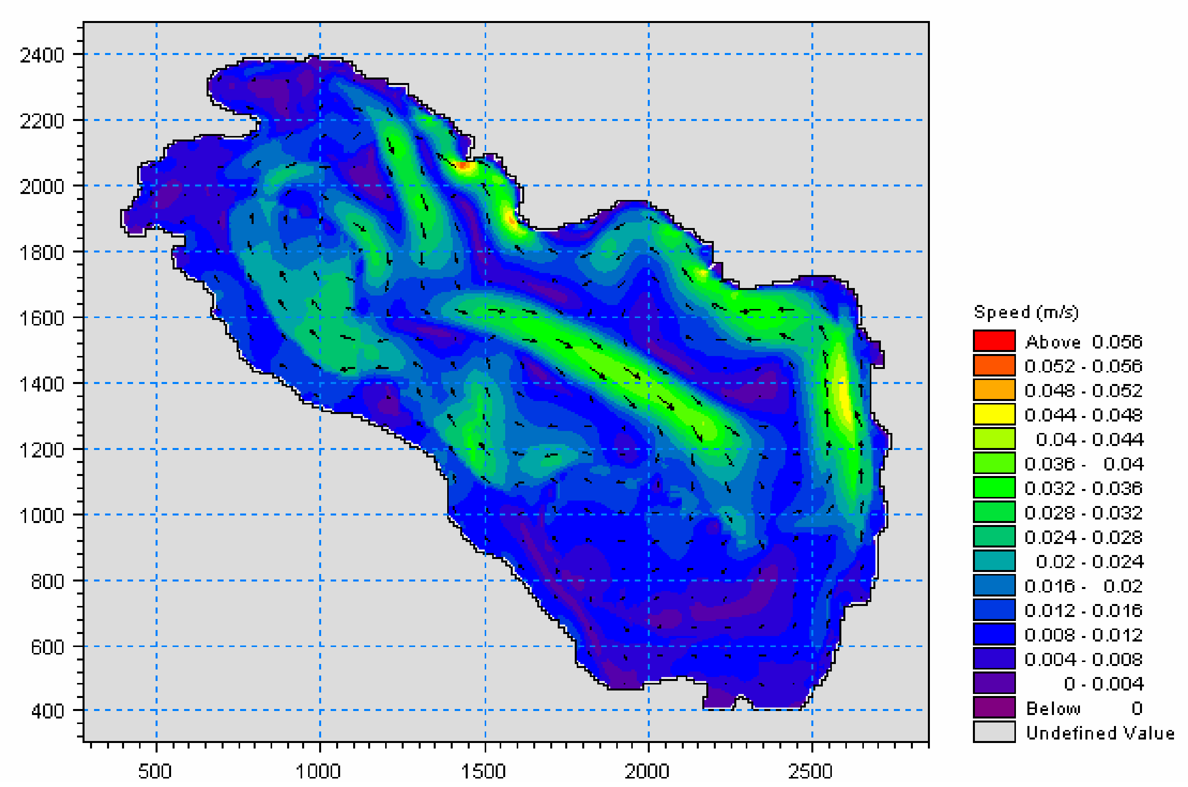

Figure 37. 5c – Krankesjöm; 1989 vegetation; Wind: south, 5m/s. Current speed

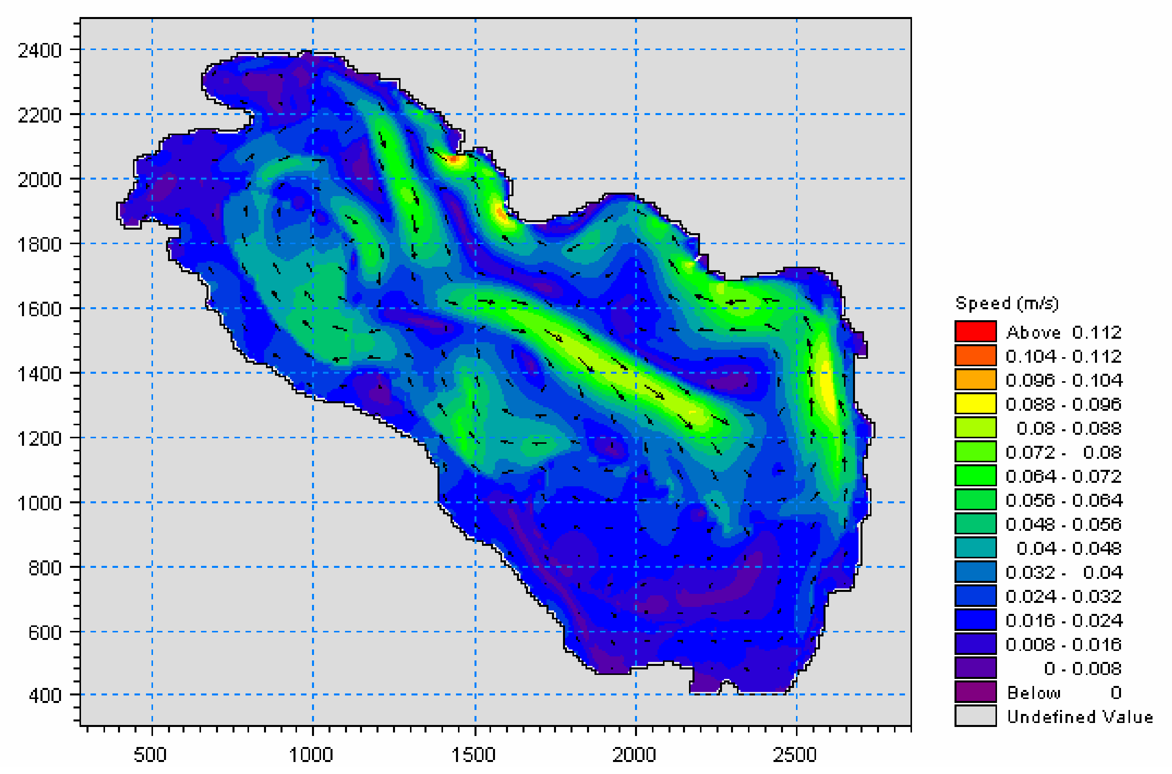

Figure 38. 5d – Krankesjöm; 1989 vegetation; Wind: south, 10m/s. Current speed

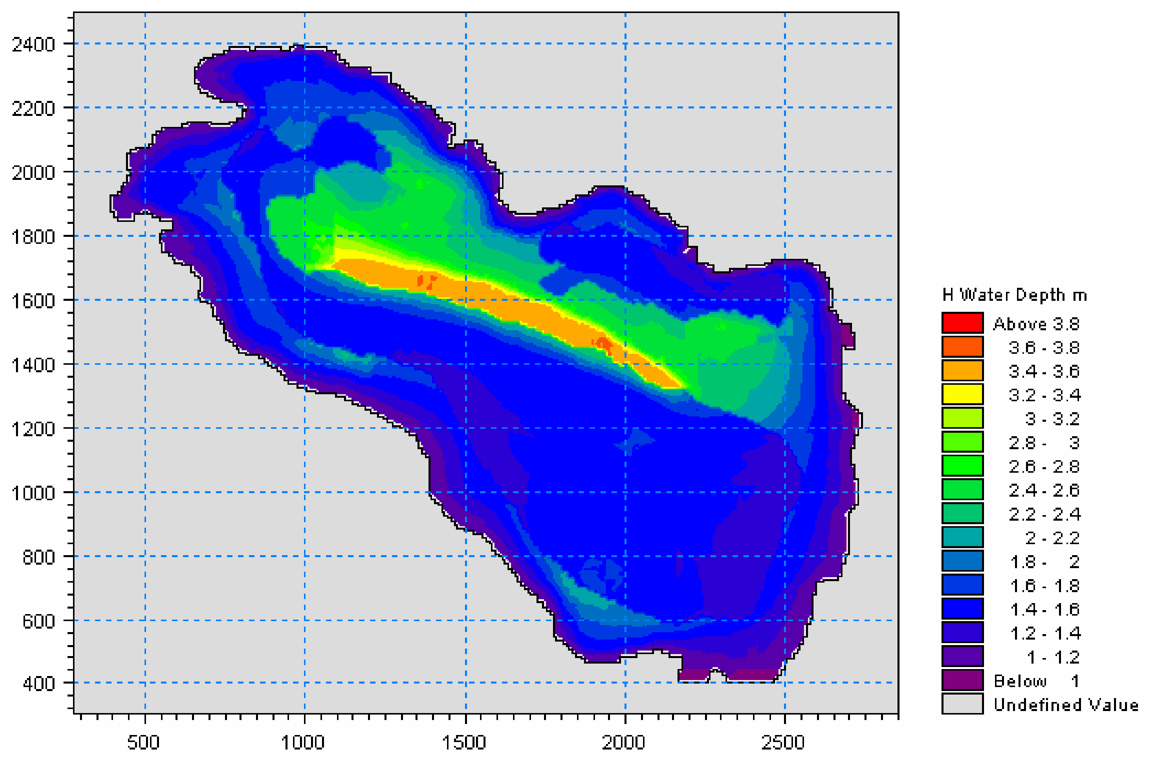

Figure 39. 6a to 6d – Krankesjön; 2004 vegetation. Water levels

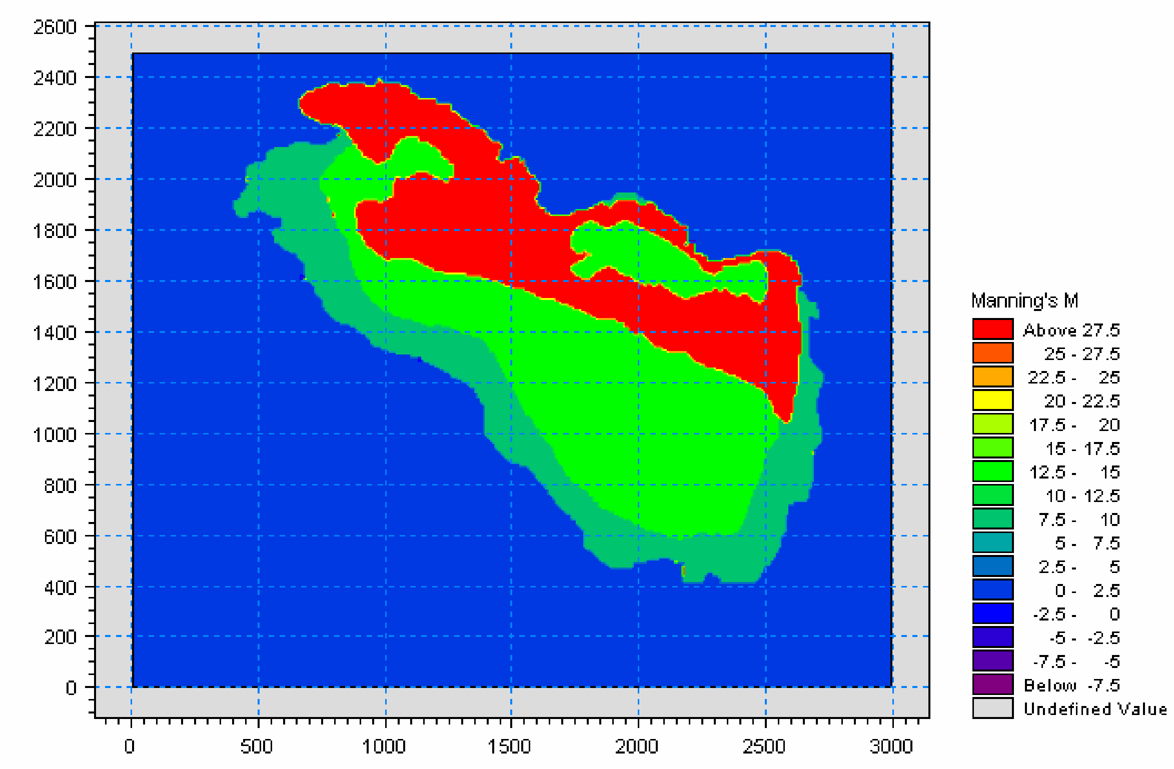

Figure 40. 6a to 6d – Krankesjön; 2004 vegetation. Manning values

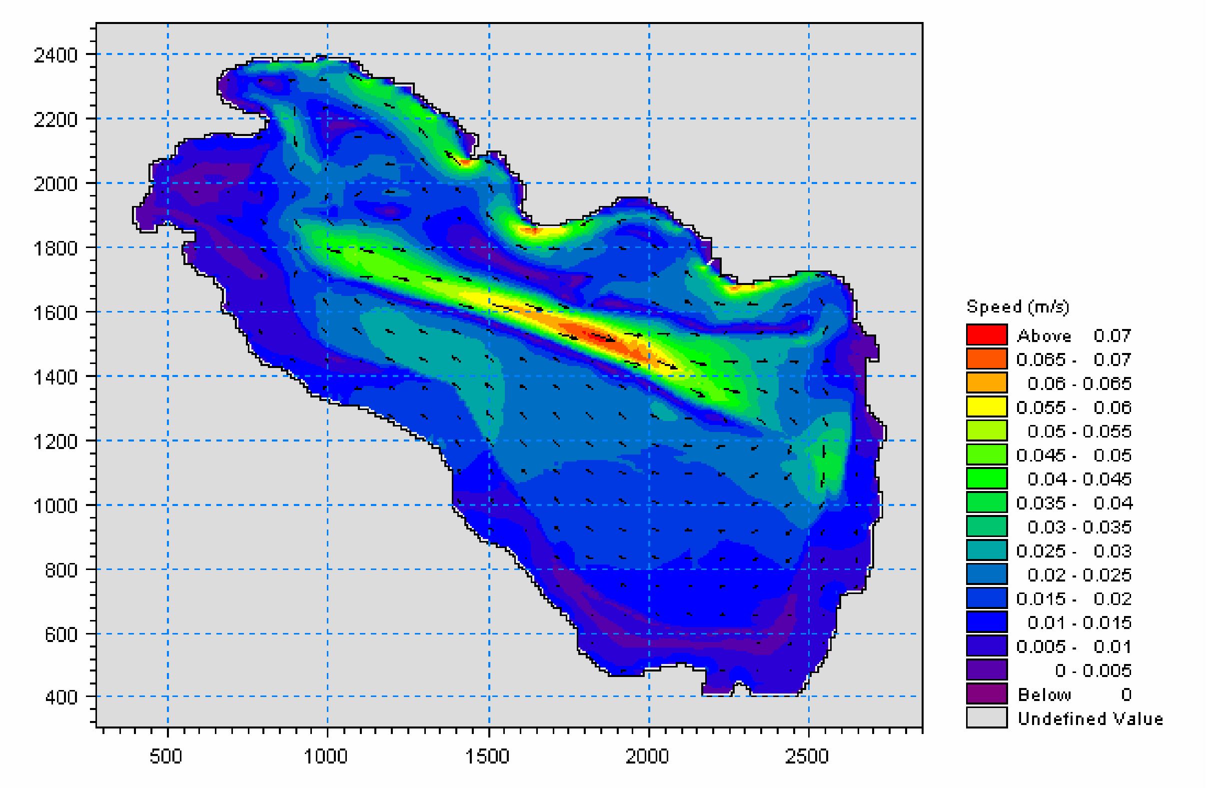

Figure 41. 6a – Krankesjön; 2004 vegetation; Wind: east, 5m/s. Current speed

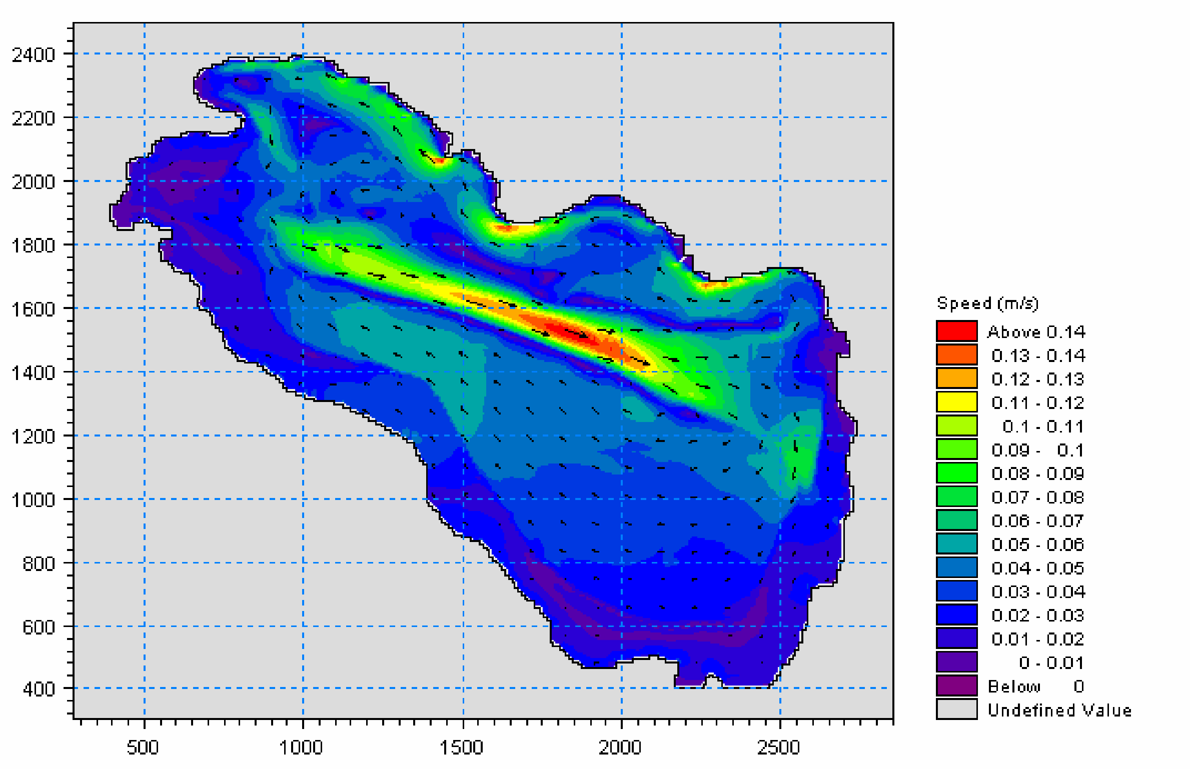

Figure 42. 6b – Krankesjön; 2004 vegetation; Wind: east, 10m/s. Current speed

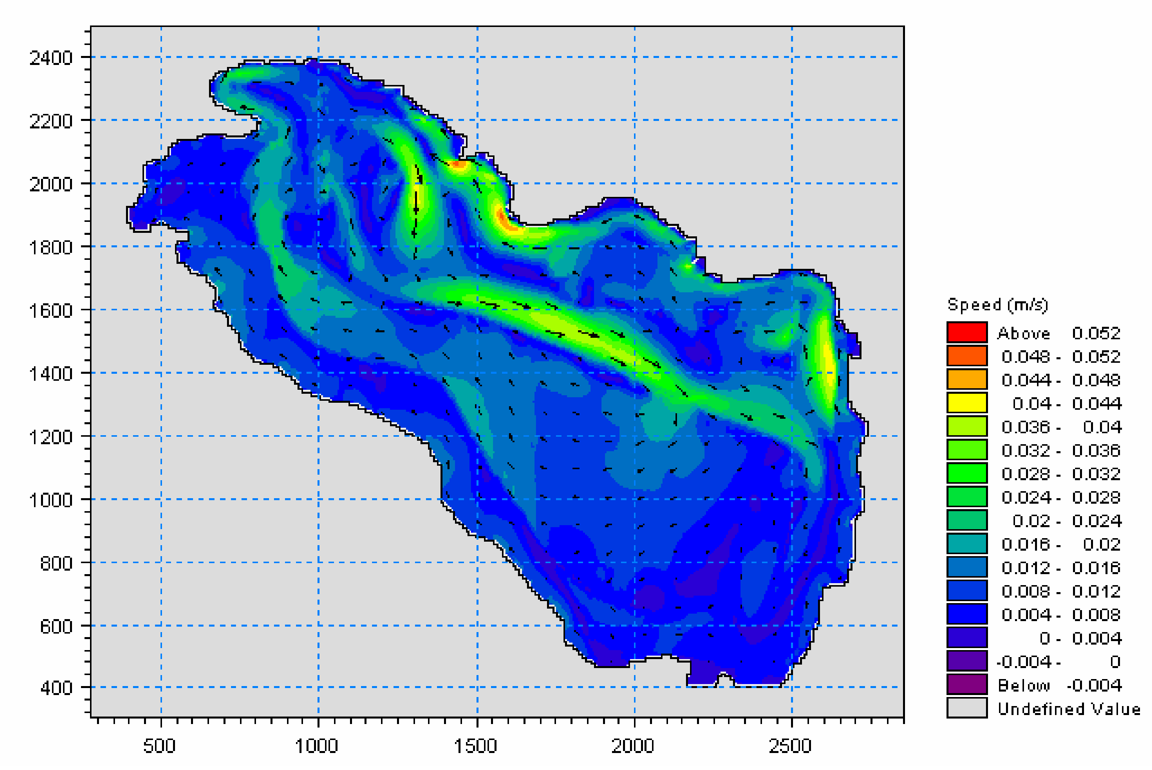

Figure 43. 6c – Krankesjön; 2004 vegetation; Wind: south, 5m/s. Current speed

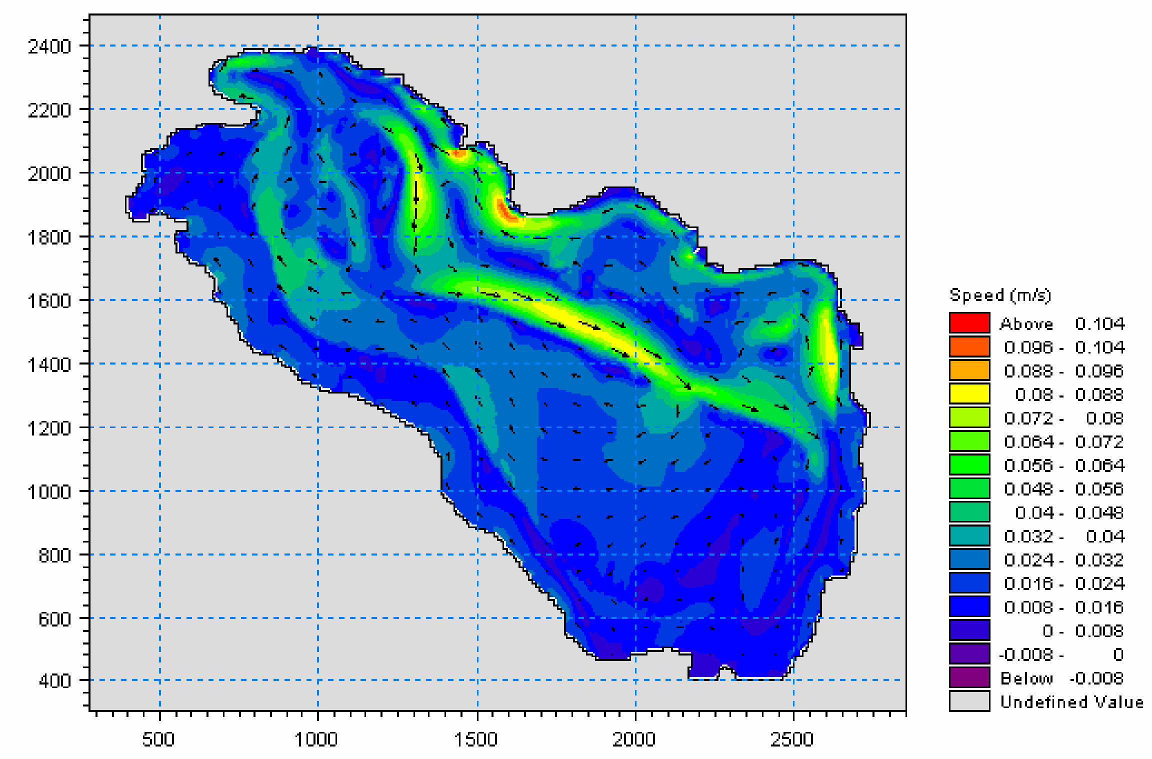

Figure 44. 6d – – Krankesjön; 2004 vegetation; Wind: south, 10m/s. Current speed

5 FIELD MEASUREMENTS

As part of the process to calibrate the model, it was necessary to conduct some field measurements. As stated before, the lake Krankesjön was selected for such measurements, not only it as fulfils the necessary requirements, being a small shallow lake with a strong presence of vegetation, but also due to its proximity to Lund.

Lake Krankesjön (see Figure 45) is situated in Scania (55 42´N, 13 28´E), in the southern part of Sweden. Its drainage area covers approximately 53 Km^2, of which the lake area makes up 7% and forests 15%, according to the Swedish Meteorological and Hydrological Institute, SMHI.

The soil is dominated by sand and low-moor peat, and although it is poor on nutrients when compared with other soils in the region, most of the lake's drainage area has been used for agriculture during the last centuries. Nowadays the whole drainage area belongs to the military, and the previously cultivated area is now used mostly for grazing cattle (Link 7).

Figure 45. Lake Krankesjön. (Foto: Charlotta Lövstedt)

One interesting characteristic of Lake Krankesjön is its historical shifts between two alternative states, one of which characterised by submerged vegetation and clear water, and the other state by turbid water and sparse submerged vegetation (Link 7). This makes it therefore a perfect example of how the presence of vegetation in shallow lakes can change along time, and thus influence in the hydraulic system.
The main purpose of the measurements made was to register current speeds in different locations of the lake, where different vegetation scenarios were expected, and thus different results, to be later used in calibration.

In order to obtain the necessary data two field trips were made, during May and June 2005. The first trip was made during the morning period, while the second was made in the afternoon.

All measurements were made from a small row boat, using specific material for each parameter being measured and the positioning was done using a GPS device.

To measure the current data a small scaled pole was first used in order to detect the current direction, which was followed by the use of a vane wheel flow sensor (manufactured by Höntzch) in order to obtain the speed values. The pole is shown in Figure 46, while the flow sensor can be seen in Figure 47.

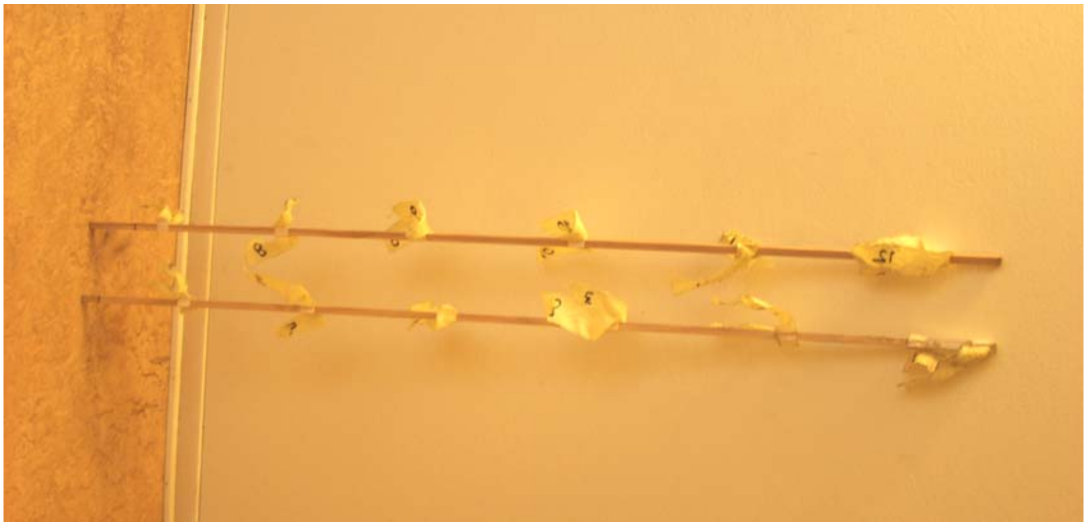

Figure 46. Scaled pole used to detect the current direction. (Foto: Charlotta Lövstedt)

Figure 47. Vane wheel flow sensor (Höntzch GmbH)

The principle of measurement of the sensor used, known as the vane wheel flow sensor, is based on the fact that a vane wheel rotates at a speed proportional to the flow velocity of the fluid into which it is immersed. The rotational speed is almost independent of density, pressure and temperature of the medium (Höntzsch GmbH [flow measuring technology] – Link 8).

The measurement of the vane wheel rotation is done by means of a proximity switch, which allows the measurement to be achieved without introducing any braking effect on the vane wheel, and therefore not affecting its rotation speed (Link 8). By fitting a further proximity switch, sensing of the direction of the vane wheel rotation and the indication of the +/-direction of flow is also possible, though in this work that was not available.

Determined by its light weight, the vane wheel rotational speed adapts to velocity changes in the order of milliseconds, even when being used in gases (Link 8), which ensures that it will have a fast response to current changes, although it also makes it harder to get a stable reading in low current speed environments such as small shallow lakes.

In this specific case the values measured by the vane wheel sensor were registered in the instrument displayed in Figure 48, the µP-Flowtherm, which does not support direction flow measuring – and thus the use of the pole. The values shown in the µP-Flowtherm are displayed in m/s.

The process of current speed measuring is then to determine the current direction with the pole, and then simply register the values indicated by the µP-Flowtherm after placing the vane sensor accordingly to the direction indicated by the pole.

Figure 48. µP-Flowtherm. (Höntzch GmbH)

Results

The measurements of current speed made in the Lake Krankesjön are summarized in Tables 3 and 5. As can be seen from the tables, the measurements were not made in the same way in both days. In table 3, referring to the 11th of May, there are readings for North, South, East and West, while in table 5, from the 2nd of June, only the actual current direction was measured. This was due to the fact that on the 11th the wind was very low, as shown in table 4, which made it difficult to detect the preferential current direction, and thus the different tests in different directions.

In table 5 three different depths can be found for each location, corresponding to the total depth [1], the depth to the vegetation top [2], and the measurement depth [3], as illustrated in Figure 49.

The points were the measurements were made were registered by GPS and can be seen in Figure 50.

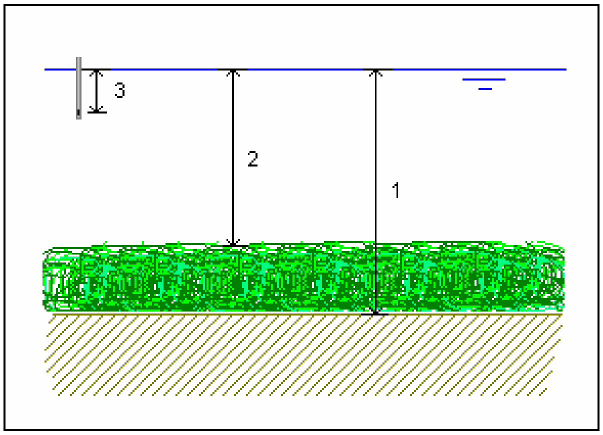

Figure 49. Measurement scheme, 2005-06-02

Figure 50. Measurement points in Lake Krankejön.

Table 3. Lake Krankesjön - current speed measurements - 2005-05-11

Reference	Time	Depth		Direction	Current speed
		Total	Measurement (from surface)		
[-]	[-]	[m]	[m]	[-]	[m/s]
G01	10:55	1,50	0,50	N	0,03
		1,50		E	0,01
		1,50		S	0,01
		1,50		W	0,01
G02	11:30	1,70	0,50	N	0,00
		1,70		E	0,00
		1,70		S	0,00
		1,70		W	0,00
G03	11:39	2,20	0,50	N	0,01
		2,20		E	0,01
		2,20		S	0,01
		2,20		W	0,03

Table 4. Wind Speed – Stensoffa Ecological station - 2005-05-11

Time	Avg. Wind Speed	Max. Wind Speed	Wind Direction	Time	Avg. Wind Speed	Max. Wind Speed	Wind Direction
[-]	[m/s]	[m/s]	[-]	[-]	[m/s]	[m/s]	[-]
00:30	0,0	0,9	S	07:00	0,9	2,2	SW
01:00	0,4	1,3	S	07:30	0,9	2,7	WNW
01:30	0,0	0,4	S	08:00	0,9	2,7	WNW
02:00	0,0	0,4	S	08:30	0,9	2,7	NW
02:30	0,0	0,9	S	09:00	1,3	3,6	NNW
03:00	0,0	0,0	-	09:30	1,8	4,9	NNW
03:30	0,0	0,9	S	10:00	1,8	4,9	NW
04:00	0,0	0,9	S	10:30	1,8	4,9	WNW
04:30	0,0	0,0	-	11:00	1,8	4,5	SW
05:00	0,0	0,4	S	11:30	2,2	5,4	WNW
05:30	0,0	0,9	S	12:00	2,2	6,3	NW
06:00	0,0	0,0	-	12:30	2,7	5,8	WNW
06:30	0,4	1,3	SSW	-	-		-

Table 5. Lake Krankesjön - current speed measurements - 2005-06-02

Reference	Time	Depth			Current direction	Current speed
		Total [1]	Vegetation [2]	Measurement [3]		
[-]	[-]	[m]	[m]	[m]	[-]	[m/s]
P01	14:19	0,75	0,45	0,20	SW	0,05
				0,35	SW	0,02
				0,50	SW	0,00 - 0,01
P02	15:00	1,20	1,15	0,20	SE	0,06
				0,48	SE	0,02
P03	15:32	1,20	1,15	0,20	SE	0,08
				0,50	SE	0,02
P04	15:48	0,75	0,75	0,20	SSE	0,06
				0,50	SSE	0,10
P05	16:04	0,65	0,45	0,20	SE	0,06
				0,40	SE	0,03
				0,50	SE	0,00 - 0,02

Table 6. Wind Speed - Stensoffa Ecological station - 2005-06-02

Time	Avg. Wind Speed	Max. Wind Speed	Wind Direction	Time	Avg. Wind Speed	Max. Wind Speed	Wind Direction
[-]	[m/s]	[m/s]	[-]	[-]	[m/s]	[m/s]	[-]
07:00	1,3	3,1	SSW	12:30	1,3	4,9	S
07:30	1,8	3,1	SSW	13:00	0,9	3,6	S
08:00	1,8	3,6	SSW	13:30	0,4	3,6	S
08:30	2,2	4,9	S	14:00	0,4	3,6	ESE
09:00	2,7	5,8	S	14:30	0,9	5,8	SSW
09:30	4,0	7,6	S	15:00	1,3	7,6	SSE
10:00	4,5	7,6	SSW	15:30	1,3	6,3	SE
10:30	4,0	8,5	SSW	16:00	0,4	4,5	SE
11:00	3,1	6,3	SSW	16:30	0,4	3,1	SE
11:30	1,8	4,5	S	17:00	0,9	4,0	SE
12:00	2,7	5,4	S	17:30	0,4	3,6	SE

As can be seen from analyzing the tables presented above, no significant values could be measured on the 11th of May, which was due to the very low wind currents that were present. On the other hand, several measurements were on the 2nd of June with significant values, all in the order of greatness of a few centimeters per second, which was only possible since the wind was quite different from the first day, as can be seen on Table 6.

6 DISCUSSION AND CONCLUSIONS

After analysing the results obtained by the simulations done in MIKE 21, as well as the results gathered from the field measurements, several conclusions can be made.

To start with, the results gathered from Lake Krankejön can be used to verify the different vegetation scenarios that can be found in shallow lakes. In fact, looking at the data from table 5, one can see that the height of submerged vegetation that was found ranged from non-existent (P04) to about 40% of the total depth (P01). This also shows that the studied scenario, with submerged vegetation up to 50% of the total depth is quite plausible, in particular if we consider that the measurements were made in the beginning of June, and it is therefore expectable that the vegetation will still show a significant growth.

Another immediate conclusion that can be extracted by comparing the simulation speed values and the measured speed values is that they are in the same order of greatness. One of the things that can be said about the field measurements is that the precision in the µP-Flowtherm could have been inadequate for such slow currents, as the smallest reading interval was of the same order of greatness of the readings themselves, but on the other hand, all measured values were in the order of 0-10 cm/s, which is consistent with the values given by the simulations. As for the direction of the current, no significant conclusion can be made, as both the runs and the field measurements showed that the whole cell system is greatly affected by the wind conditions and presence of vegetation, making it impossible to directly relate both, since to do that it would be necessary to have the same vegetation cover in the lake and in the model, as well as the same wind conditions. This can easily be seen by comparing the different studied scenarios.

This brings us to the results given by the models, where some immediate conclusions can also be taken.

To begin with, it was clear that the wind direction can greatly affect the out coming effect of the vegetation models used. This can be seen for example looking at Figures 16 and 18, from scenarios 2a and 2b, or at Figures 30 and 32 from the case scenarios 4a and 4c. In the first case one could say that the bathymetry used is purely theoretical, but in the second case it is quite evident on how the whole circulation system is affected by the wind direction, as well as the average current speeds, that are lower in case 4c (wind from the south). This effect is caused by the irregular bathymetry, as it allows the wind to have greater effect on the current if along the bathymetry, and is also present in the unvegetated scenarios, seen in Figures 24 and 26 for the 3a and 3c cases.

Since one of the modelling techniques consisted of changing the bathymetry to simulate submerged vegetation, one could expect this to happen, as it did. Comparing Figures 24 and 30 from cases 3a and 4a, it is possible to notice how the introduction of vegetation lowers the current speed in its surroundings.

At this point, after realising that the model used to simulate submerged vegetation does influence the local hydrodynamics, it is necessary to look into its validity. As a reminder, submerged vegetation was modelled as an additional volume in the bathymetry, just as a “hill”, with high resistance to flow when compared to the bed sediments. This meant that no flow whatsoever would be going through it.

Part of this has already been confirmed, as highly dense vegetation going up to 40% of the water depth was found during the field measurements, but additionally, as measured in points P01 and P05, with vegetation using 40% and 30% of the total depth respectively, the current speed near the top of the vegetation (5 cm within it) showed to be very low, going from no movement to values around 1or 2 cm/s. In other words, the measurements made showed that the assumption made is not entirely valid, at least when referring to the upper area of the vegetation, but it represents a reasonably good approximation. Having in mind that these models were being tested to be used as primary replacements for more complex and advanced methods, one must say that the results obtained were satisfactory.

Looking further into the simulations, it is necessary to pay attention to the results of the emerged vegetation (such as reed belts) models.

Starting with the square lake models, it is quite evident that no significant difference occurred between the cases 1a and 2c (Figures 12 and 19) or 1b and 2d (Figures 14 and 22). This of course has to do with the chosen bathymetry, but mostly with the fact that since only the bed resistance was changed, the effects on the flow will be limited to a certain level. This means that if the water surface is too high, the model will not be a good representation of emerged vegetation. Moreover, if we keep in mind that the vegetation being simulated is emerged, it becomes clear that its effect should be felt throughout the whole vertical, and not only to a certain level. This suggests that it might be necessary to increase the bed resistance even more, or to apply it only up to a certain water level. In this particular case, the initial surface level used in MIKE21 was 1.5 meters for both the submerged and emerged square lake models, but still, and since the model being used is a vertically integrated model, one should still expect a decrease in the water speed, as the value displayed represents an average, which should decrease even if the rugosity effect is only felt up to a certain water level.

However, and when analysing the results obtained for the Lake Krankesjön bathymetry, this problem does not occur. In fact, comparing each of the scenarios 4a and 5a, to 4d and 5d, where the only difference is the introduction of the emerged vegetation (see Maninng files, Figures 29 and 34), it is quite evident that there is a reasonable decrease in the current speed, as seen for example from cases 4a to 5a (Figures 30 and 35), around the coordinates [1400, 1300] where the average speed decreases about 6 times (from 6 cm/s to aprox. 1cm/s).

This suggests that the bathymetry has a great influence on the validity of this model, especially considering that the water levels in these areas are also in the order of greatness of 1.5 meters, just as in the square lake scenarios.

One important thing to do now should be to try to validate the model using the data collected from the field measurements. However, it was not possible to make measurements inside the reed belts, due to their high density, which creates an additional difficulty in evaluating this specific model. It is true that the effect in the real lake bathymetry was as expected, as the current speed decreased, but on the other hand the square lake simulations showed that this model may have important limitations.

Finally, it is also interesting to compare the two most extreme situations: the one with no vegetation and the one with the vegetation cover from 2004 (cases 3a to 3d and 6a to 6d). Once again it is evident that the wind direction plays an important role in how vegetation affects the hydrodynamics, as although clear, these effects change with the wind direction. Comparing the first wind scenario for example, from cases 3a and 6a

(Figures 24 and 41), there is a significant change in the current speed, as seen for example around the coordinates [1200; 1300], where in case 3a this area is a path for preferential flow, while for the correspondent 6a the current speed is close to zero.

On another hand, comparing cases 3d and 6d (Figures 27 and 44), it is visible that the effect of vegetation changes not only the current speed, but also has a significant influence in the cell system, as seen in the southeast part of the lake. An interesting difference seen between these two cases, is that the introduction of vegetation eliminates the areas of current speed lower that 0.01 cm/s seen in case 3a, which suggests that the effect of vegetation in the preferential flow paths and cell system can be used to force water circulation, which can be very important in systems such as wetlands used for water treatment.

After evaluating the results obtained both by the runs and by the field measurements several suggestions can be made, both for subjects of further study, and to better evaluate the use of these techniques.

To start with, and having in mind the models that were used here, it would be interesting to study how can they can be used with different parameters, such as by changing the percentage of the total water level estimated as vegetation, or by testing the effects of different resistance values.

Regarding the emerged vegetation model, and the limitations it appears to potentially have, it would be a good suggestion to do further studies with this technique, mainly on the effects of the usage of different bathymetries, and also to have significant field data to better validate it. Another very important change that can be made to this model has to do with the wind friction. Since the initial idea was to change only simple parameters, the wind friction was always assumed to be constant. In emerged vegetation scenarios this is obviously not corresponding to reality, meaning that a significant improvement to the model could be to alter this parameter as well. It will however represent an increase in the complexity of the model, which goes a bit against the purpose of these techniques.

Finally, and considering the overall results obtained, it seems that the models can be used as good approximations of vegetation, in particular the one of submerged vegetation, for the tested conditions, while the emerged vegetation model should be used with some caution, and preferably with the further studies suggested.

It would also be interesting to perform a cost and time comparison between the usage of these simple techniques to predict the effects of vegetation and the actual use of vegetation models, and the additional information gathering that they require.

Finally, it is important to keep in mind that the models tested here consisted only of affecting the input data, which makes them independent of the software being used. It may of course be necessary to make some fine adjustments for each software product, but overall the modelling being made should remain a good approximation regardless of the software chosen.

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