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Numerical modeling of water and ice dynamics for analysis of flow around the Kiezmark bridge piers

Civil and Environmental Engineering
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Aim of the study

How the results obtained from a mathematical model can support decision-making when designing hydrotechnical objects

Bridge is planned in km 930+010 of the Vistula River (express road from Gdansk to Warsaw)

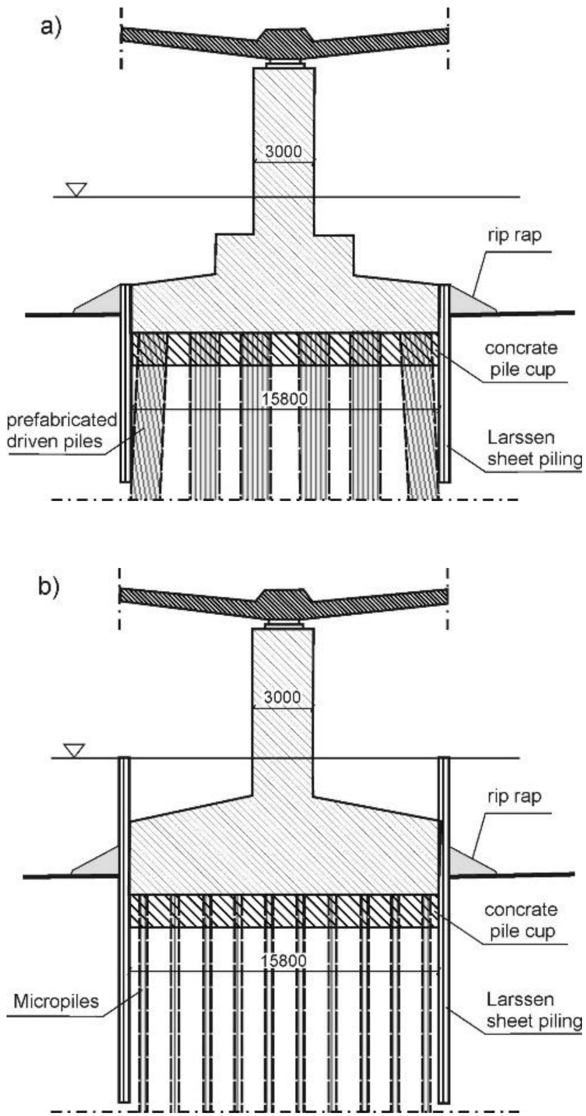
12 spans supported on piers

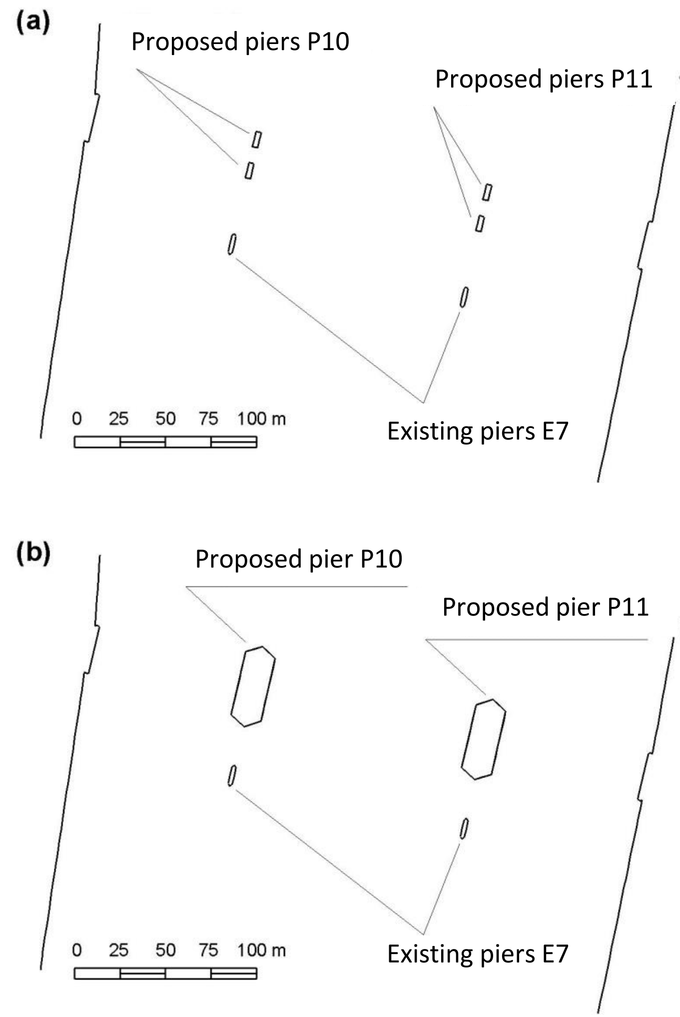
Main span over the Vistula River (130 m)

Located over the waterway

source: GDDKiA

Piers layout





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Hydrodynamic calculation

Two–dimensional shallow water equations (SWE) model

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} + \mathbf{S} = 0 ,$$

$$\mathbf{U} = \begin{pmatrix} h \\ uh \\ vh \end{pmatrix}, \quad \mathbf{S} = \begin{pmatrix} 0 \\ -gh\left(S_{ox} - S_{fx}\right) \\ -gh\left(S_{oy} - S_{fy}\right) \end{pmatrix} \quad \mathbf{E} = \begin{pmatrix} uh \\ u^2 h + 0.5gh^2 \\ uvh \end{pmatrix}, \quad \mathbf{G} = \begin{pmatrix} vh \\ uvh \\ v^2 h + 0.5gh^2 \end{pmatrix}.$$

h = water depth,

u v = horizontal components of the velocity,

S_{ox} S_{oy} = bed slope terms,

S_{fx} S_{fy} = hydraulic slopes defined using Manning formula,

g = acceleration due to gravity

integration in space → finite volume method

integration in time → explicit two step finite difference scheme

Bridge pier under construction

cofferdam (June 2016)

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Bridge pier under construction

concrete works (November 2016)

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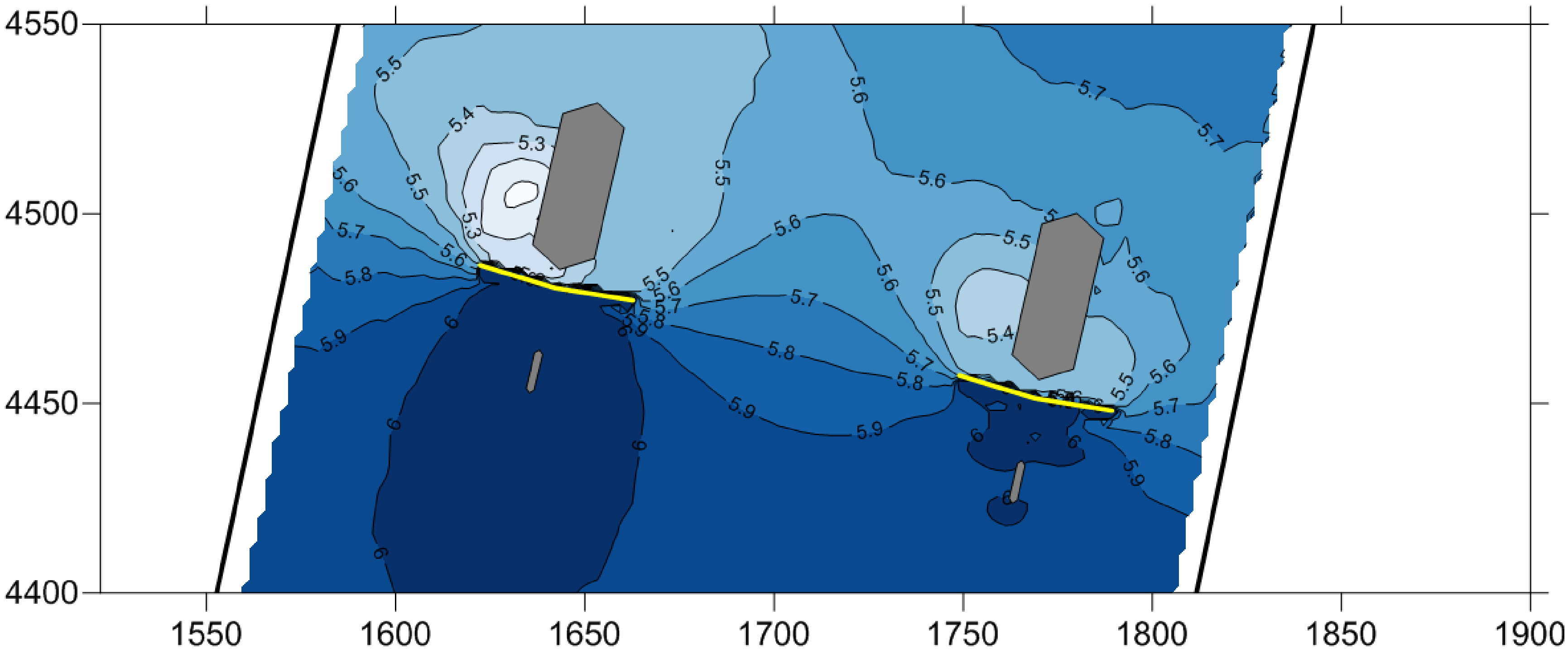
100-year flow ($Q_{1\%}$) with cofferdams
Water surface elevation [m]



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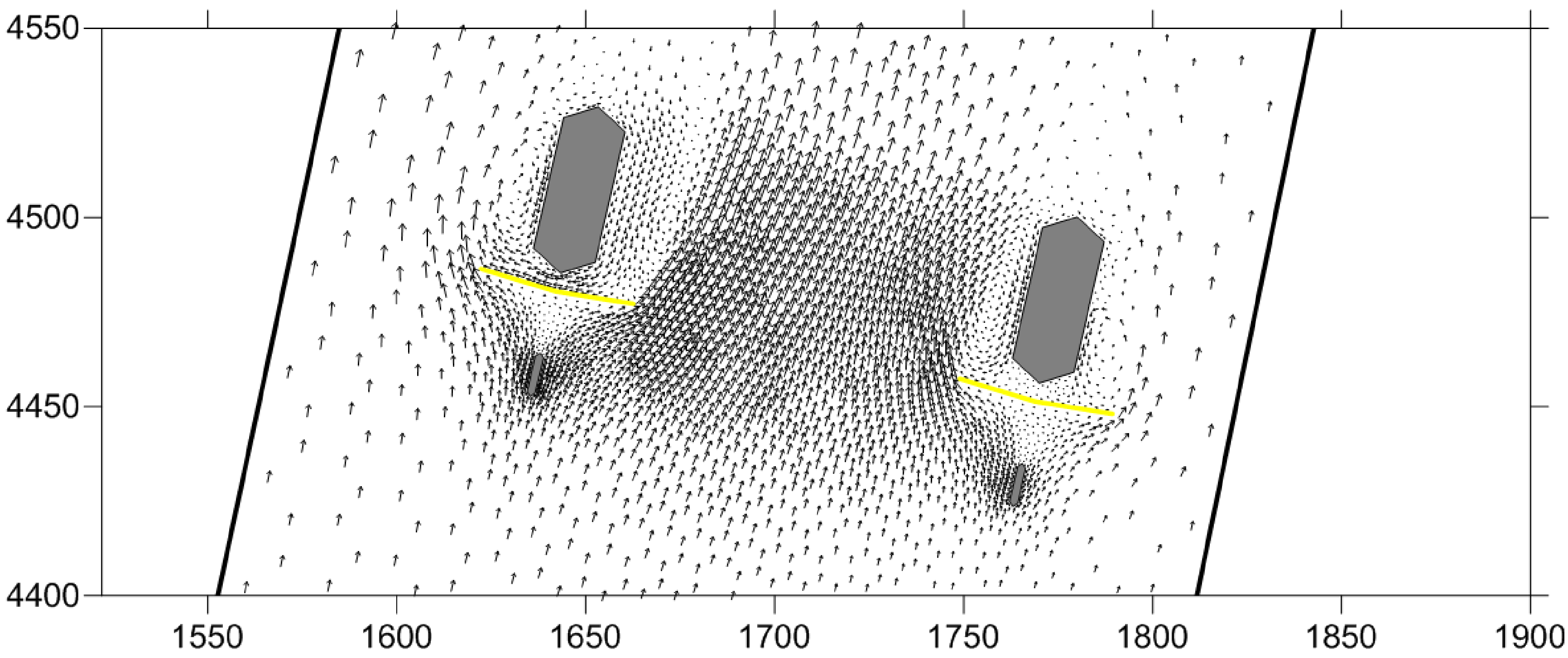
100-year flow ($Q_{1\%}$) with cofferdams
Water velocity distribution



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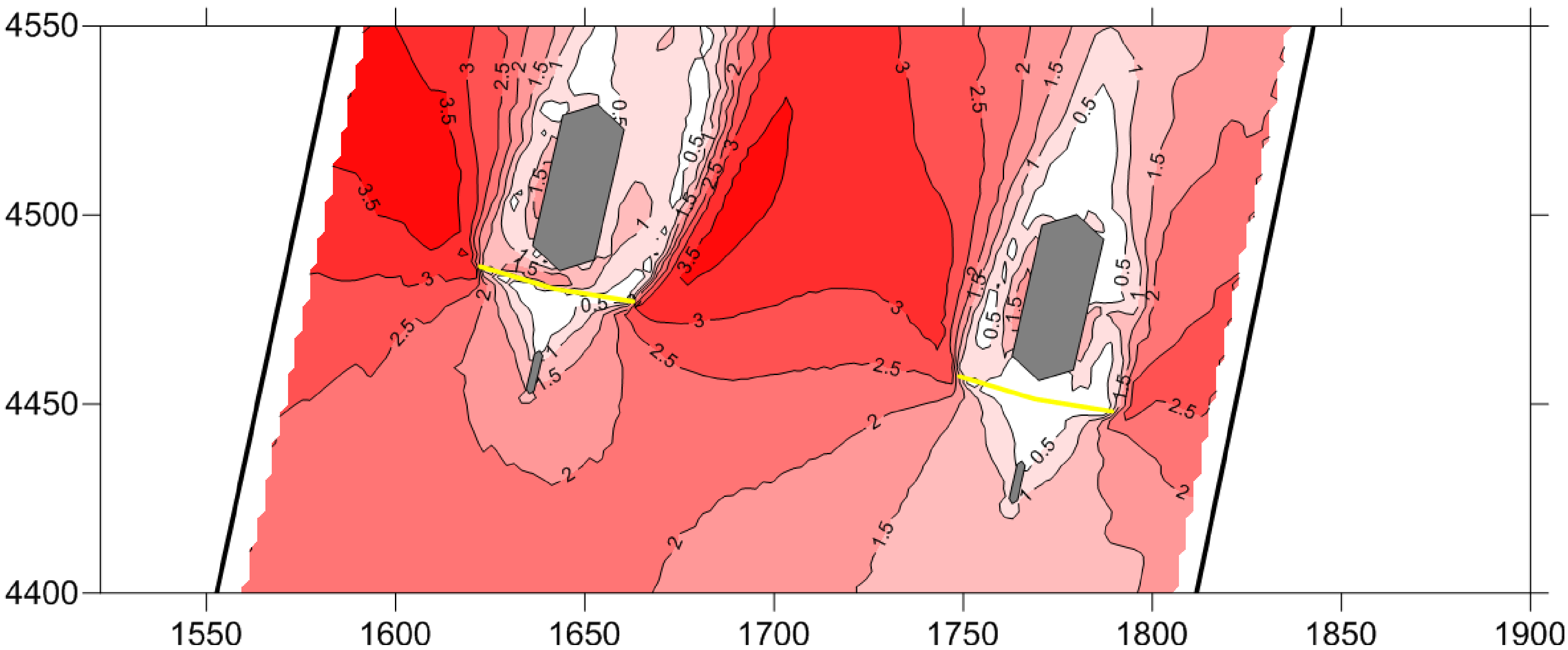
100-year flow ($Q_{1\%}$) with cofferdams
Water velocity magnitude [m/s]



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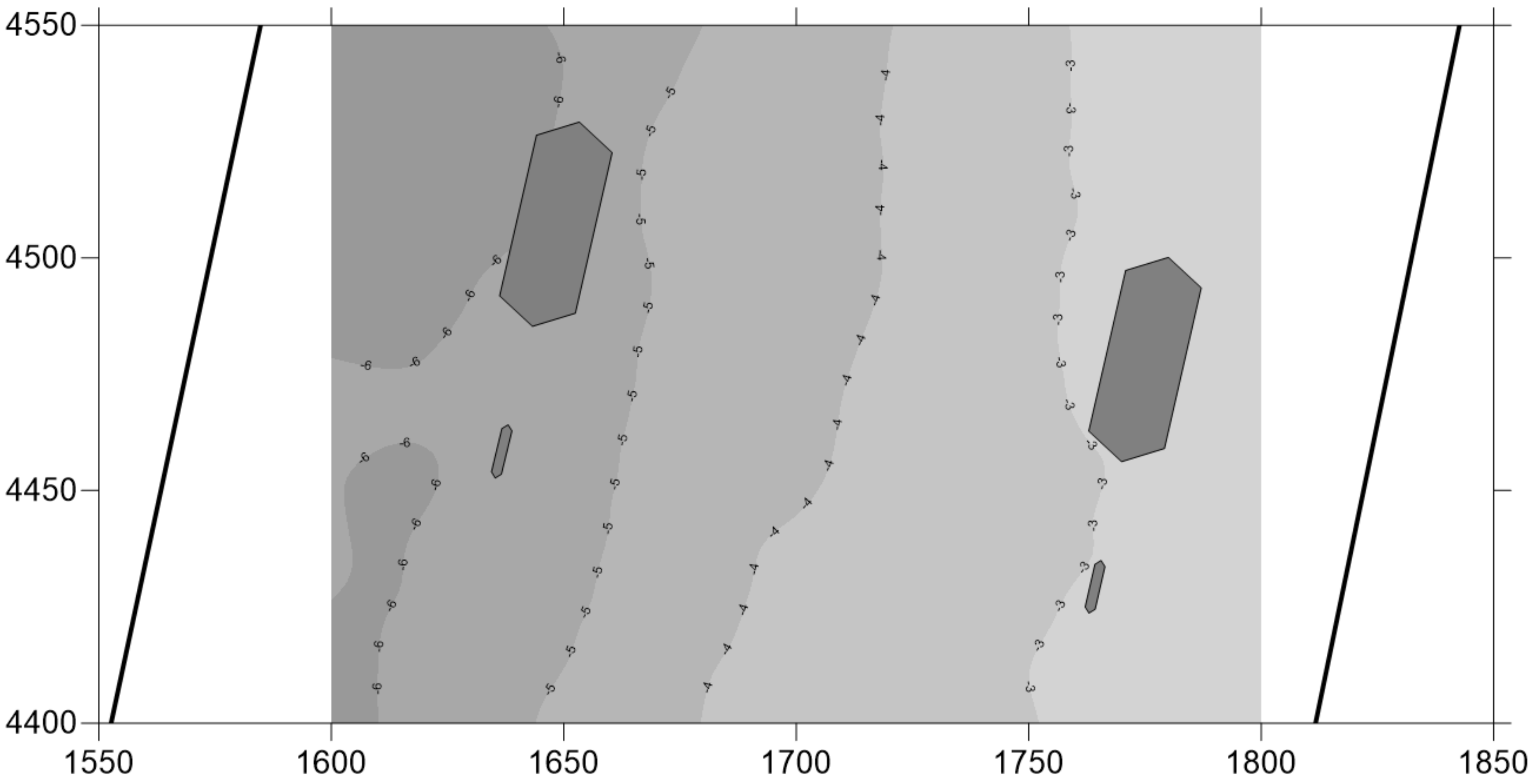
River bathymetry
(prior to the bridge construction)



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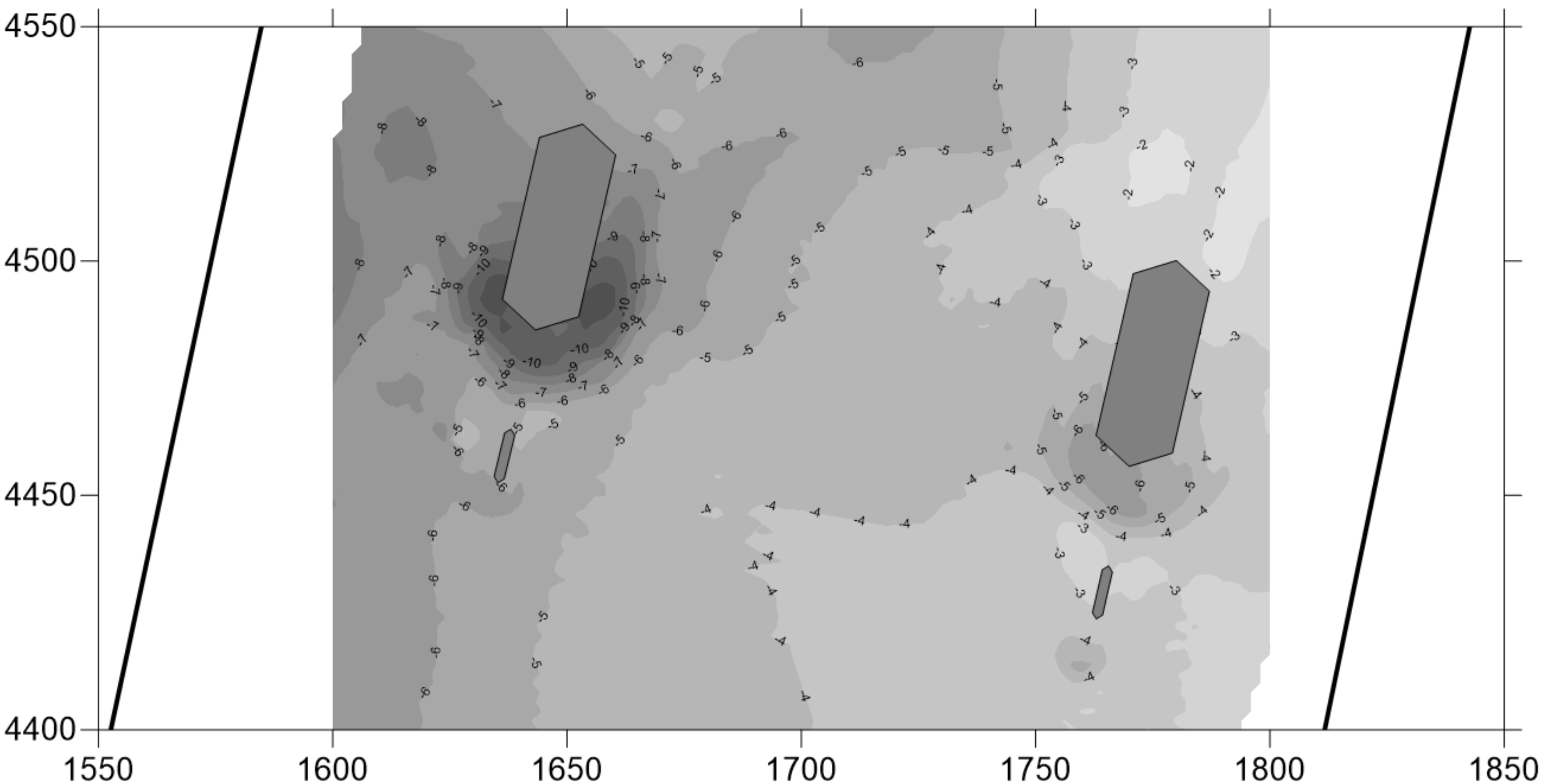
River bathymetry
(measured: December 2016)



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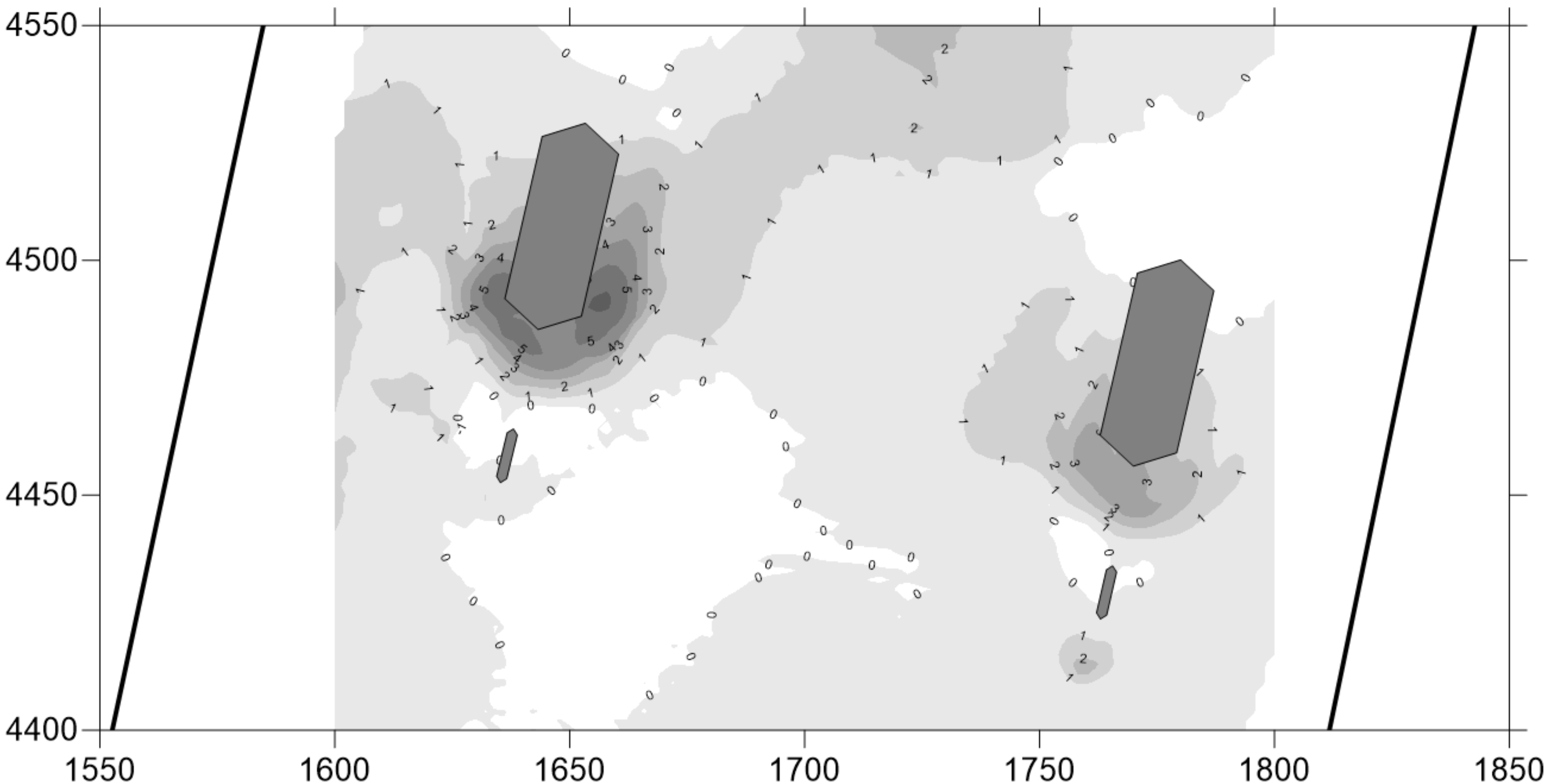
Bed erosion [m]



River ice dynamics

DynaRICE model

$$M_L \frac{d\vec{V}_L}{dt} = \vec{R} + \vec{F}_a + \vec{F}_w + \vec{G}$$

M_L = unity mass (per area) of ice particle,

$\vec{V}_L$ = ice velocity vector,

$\vec{R}$ = ice internal resistance force,

$\vec{F}_a$ = wind drag,

$\vec{F}_w$ = water drag,

$\vec{G}$ = gravity force.

Solved by SPH method with method of images implemented to the land boundaries

Force balance

$$\sum F_x = -\sigma_{xx}N\eta dy - \sigma_{yx}N\eta dx + XN\eta dl + \frac{1}{2}\tau_{wx}Ndxdy + \frac{1}{2}\tau_{ax}Ndxdy + \\ + \frac{1}{2}\rho N\frac{dh}{dx}dxdy = 0$$

$$\sum F_y = -\sigma_{yy}N\eta dx - \sigma_{xy}N\eta dy + YN\eta dl + \frac{1}{2}\tau_{wy}Ndxdy + \frac{1}{2}\tau_{ay}Ndxdy + \\ + \frac{1}{2}\rho N\frac{dh}{dy}dxdy = 0$$

X, Y = components of the ice load on the structure;

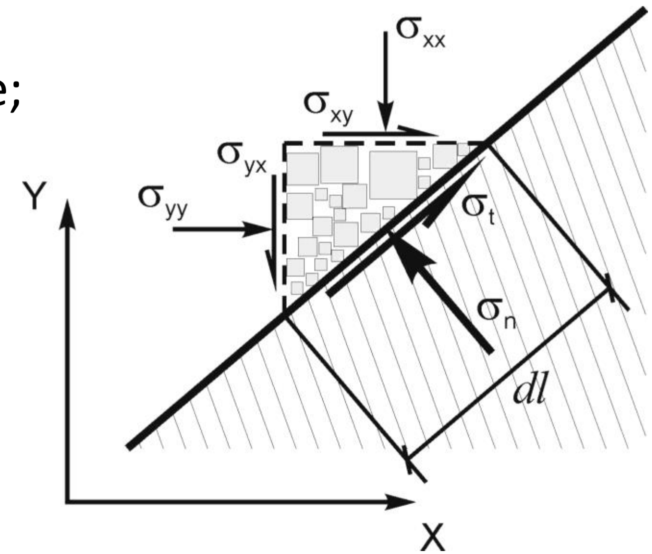
η = thickness of ice,

N = ice concentration;

τ_{ax}, τ_{ay} = components of wind drag;

τ_{wx}, τ_{wy} = components of water drag;

σ_{xx}, σ_{yy} and $\sigma_{xy} = \sigma_{yx}$ internal ice stresses



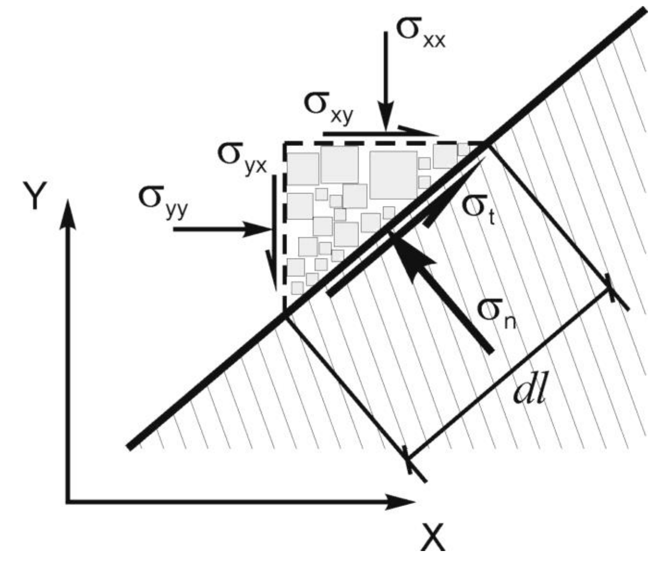
Ice load on stationary structure

$$\sigma_n = \sigma_{xx}\left(\frac{dy}{dl}\right)^2 + \sigma_{yy}\left(\frac{dx}{dl}\right)^2 + \sigma_{yx}\frac{dx}{dl}\frac{dy}{dl}$$

$$\sigma_t = (\sigma_{xx} - \sigma_{yy})\frac{dx}{dl}\frac{dy}{dl} + \sigma_{yx}\left[\left(\frac{dy}{dl}\right)^2 + \left(\frac{dx}{dl}\right)^2\right]$$

$$F_n = \sigma_n N \eta$$

$$F_t = \sigma_t N \eta$$



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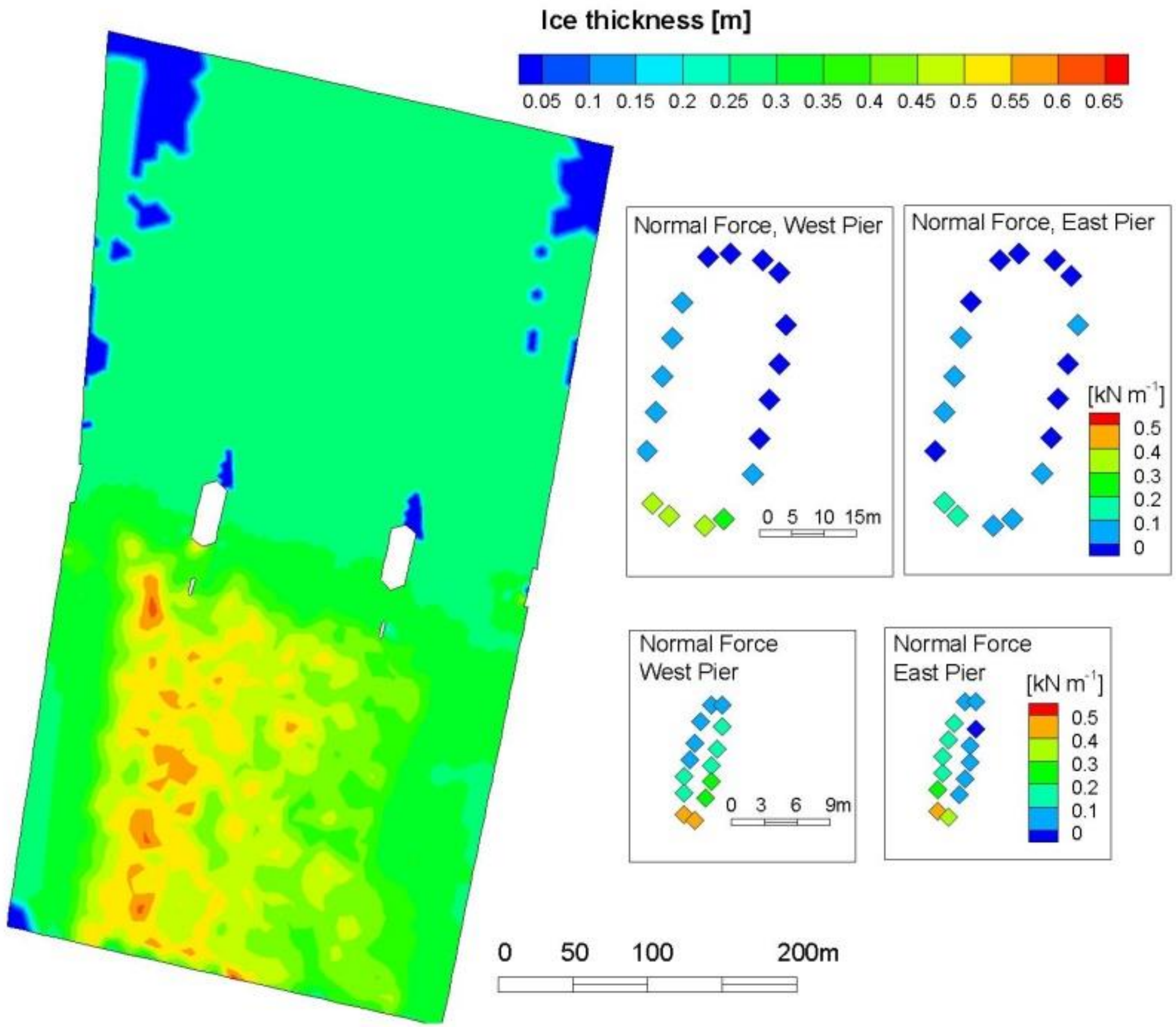
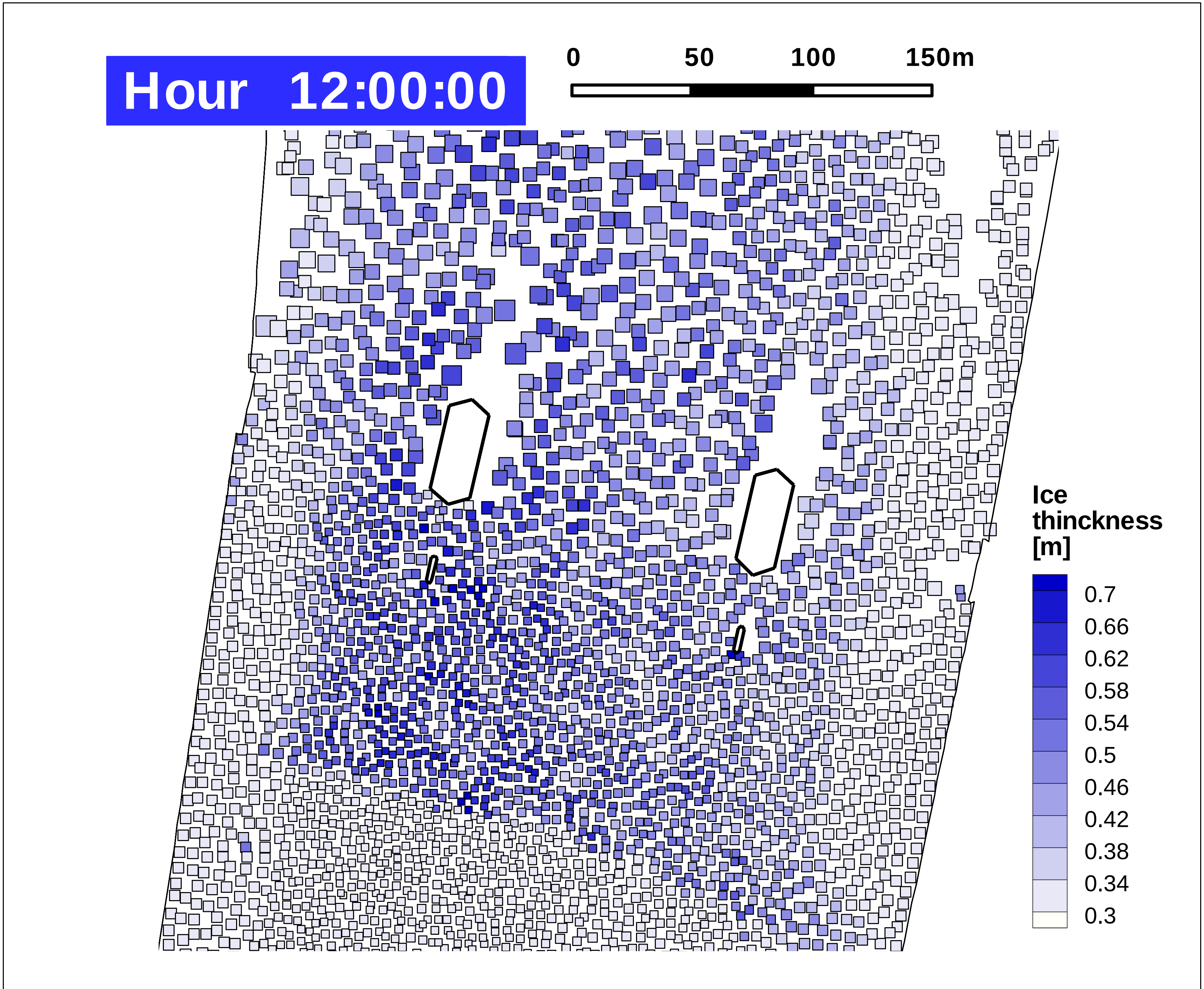
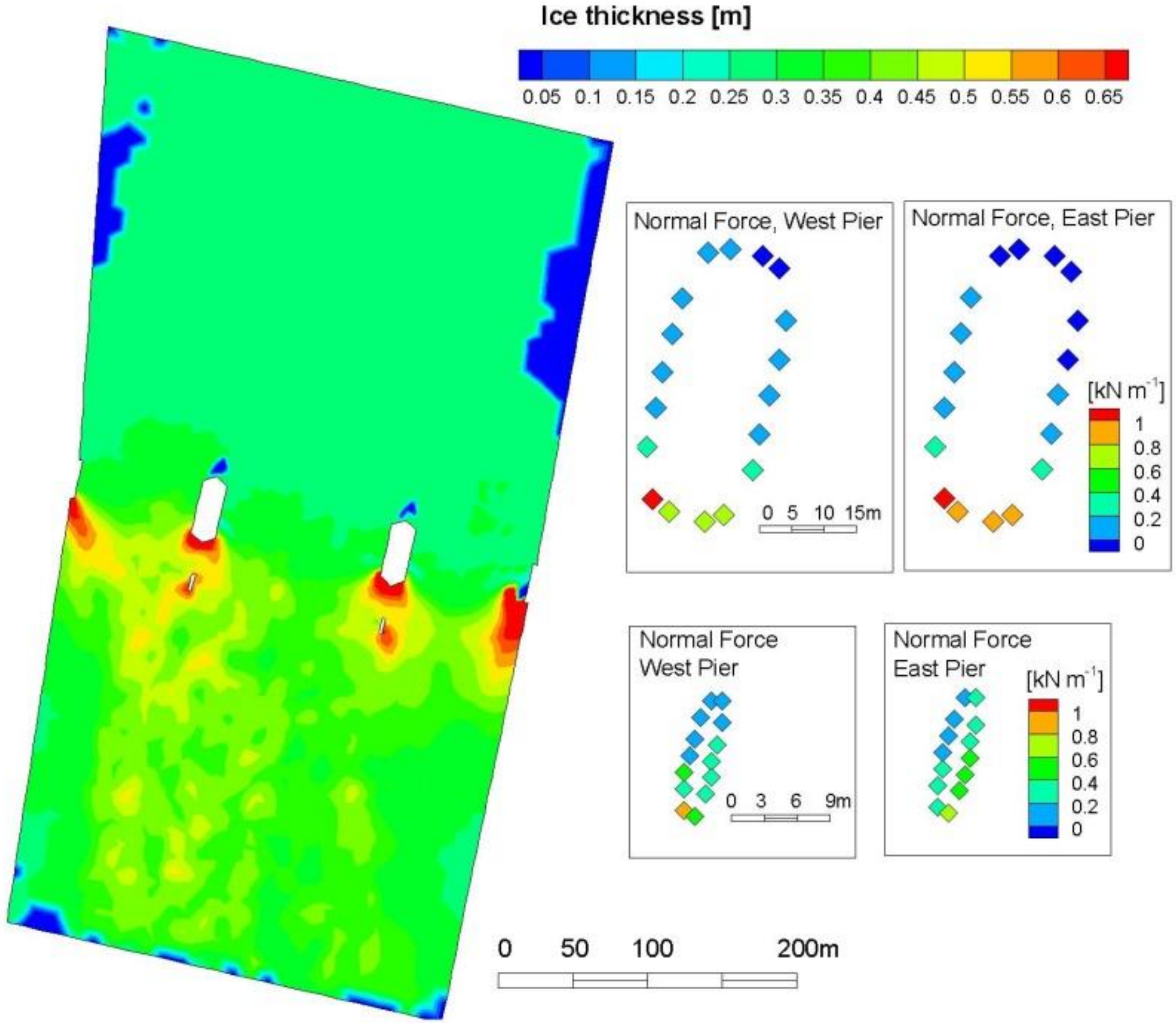
Ice thickness and ice loads
Low flow condition Q=411 cms




Hour 12:00:00
0
50
100
150m
Ice thinckness [m]
0.7
0.66
0.62
0.58
0.54
0.5
0.46
0.42
0.38
0.34
0.3

Ice thickness and ice loads
Average flow condition Q=1046 cms



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Ice condition on January 30th, 2017 west pier under construction

Courtesy: M. Naskręt, trojmiasto.pl

Conclusions

- Mathematical models are precise tools to predict possible conditions that may occur in a future structure operation.
- Results of numerical modeling was used to assess the effect of bridge piers on hydrodynamic and ice transport. The ice load on the piers was also determined
- Even though numerical modeling is generally accepted and defined as a best practice in bridge design, there is shortage of such activity in Poland.
- Insufficient structure to environment interaction analysis may lead to variety of dangerous situations including stability problems, river degradation, increased flood risk and other environmental issues.