Oddział Warszawski Polskiego Towarzystwa Matematycznego

Modelowanie rozprzestrzeniania się zanieczyszczeń termicznych w rzekach

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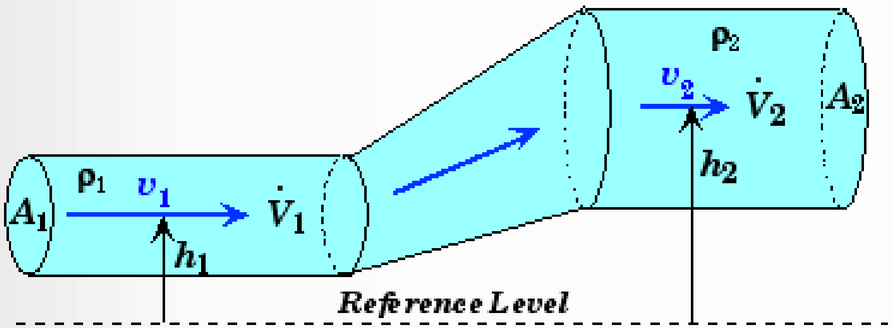
Przepraszam za polsko-angielską mieszankę językową

Uwagi wstępne dotyczące hydrodynamiki środowiskowej

Główne problemy związane z:

- brakiem „zrozumienia” wielu procesów fizycznych,
- „geometrią”,
- brakiem wielu danych (szorstkość!)

A great success behind hydraulics engineers in modeling of flows in a variety of engineering objects imposes the view that similar success is easy in the analogous river flows.



„Easy hydraulics"

There are, great differences between environmental flows and their engineered counterparts and they are revealed in terms of length scales, levels of turbulence, moveable boundaries and geometrical complexities

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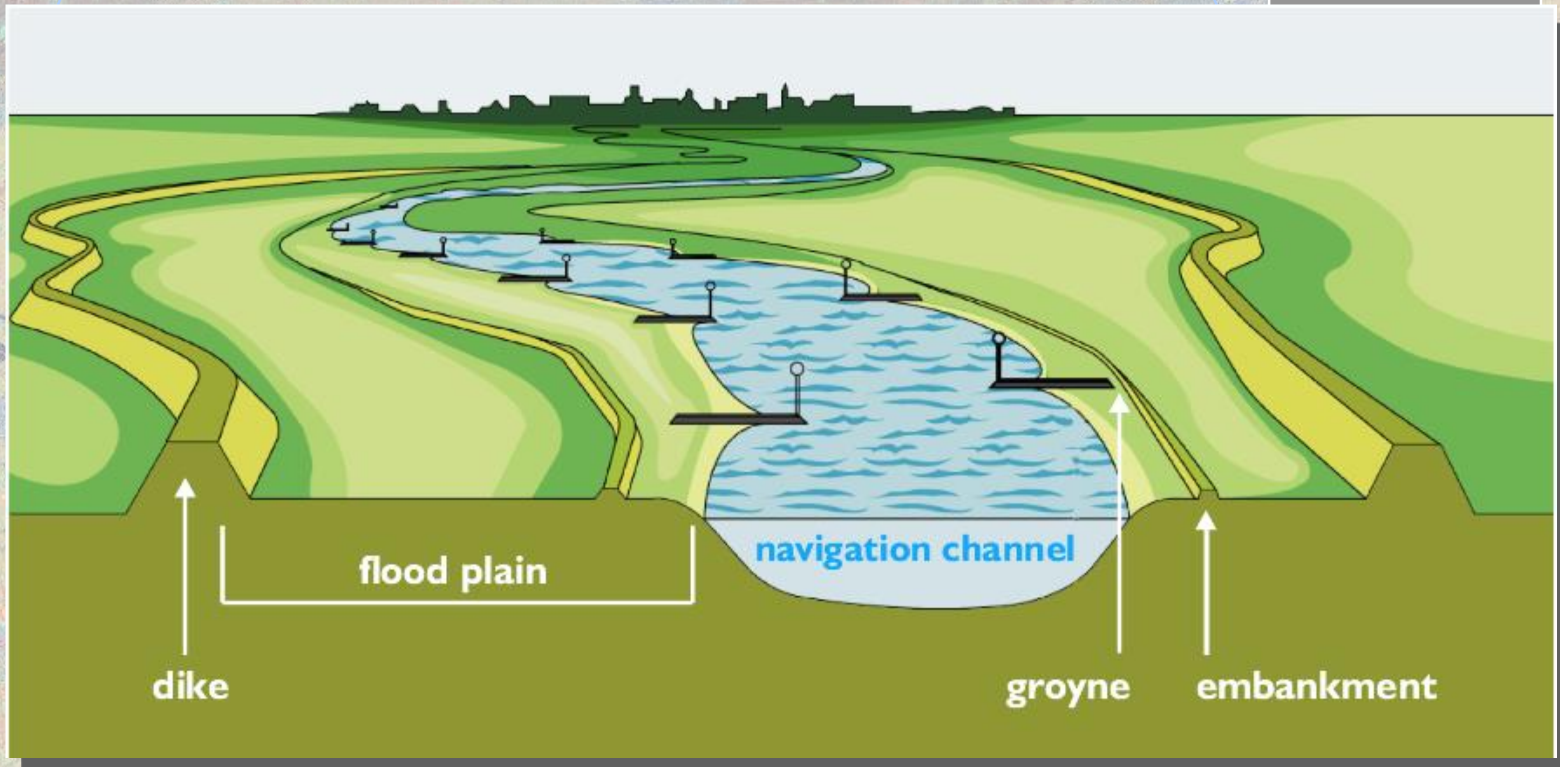
Typical Cross-section

Intervention



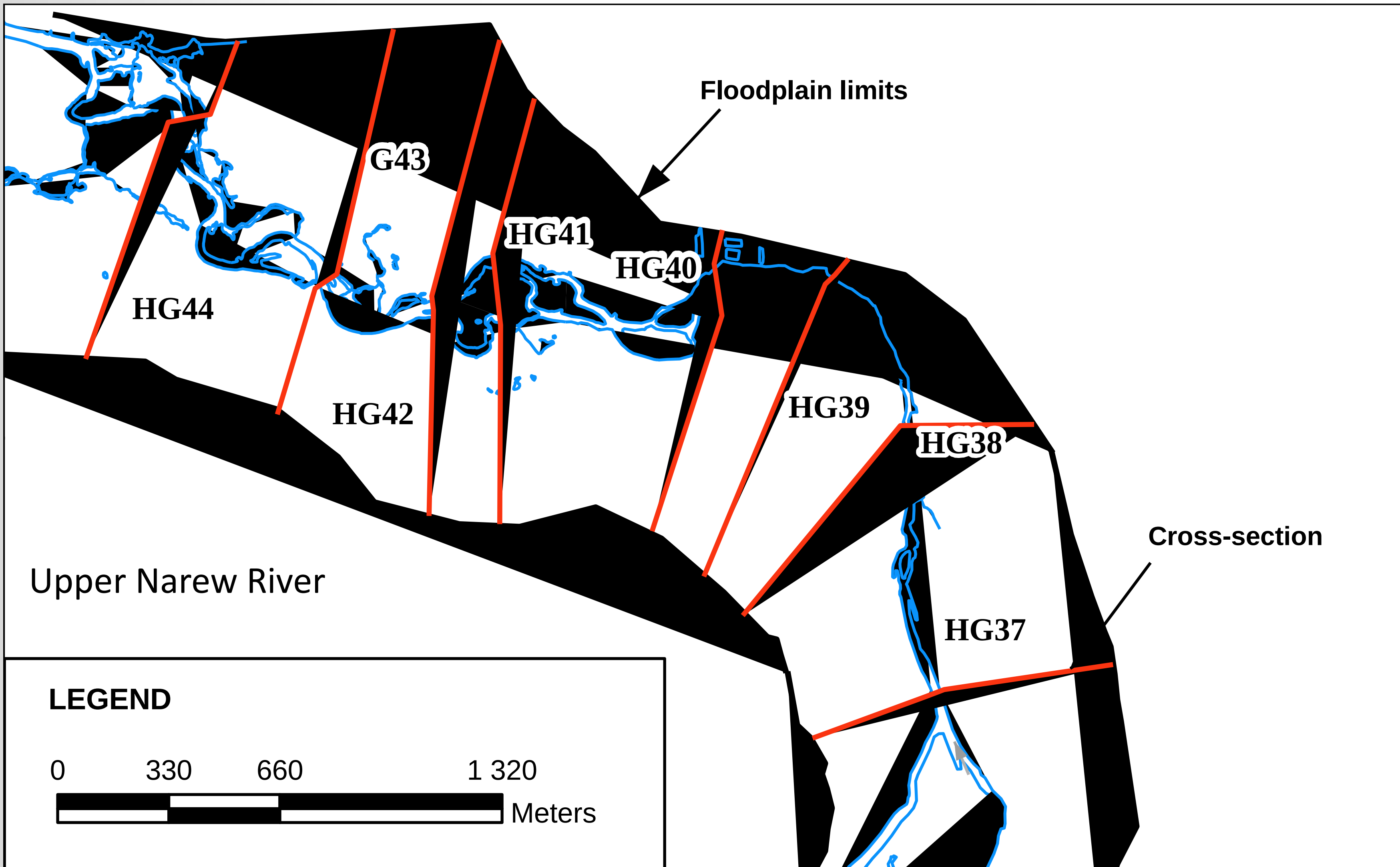
compensation) costs of land, and additional management and maintenance costs.

Return


Niezwykle złożona geometria
zwłaszcza w terenach
mokradłowych

Cross-section survey layout

Non-unique solutions



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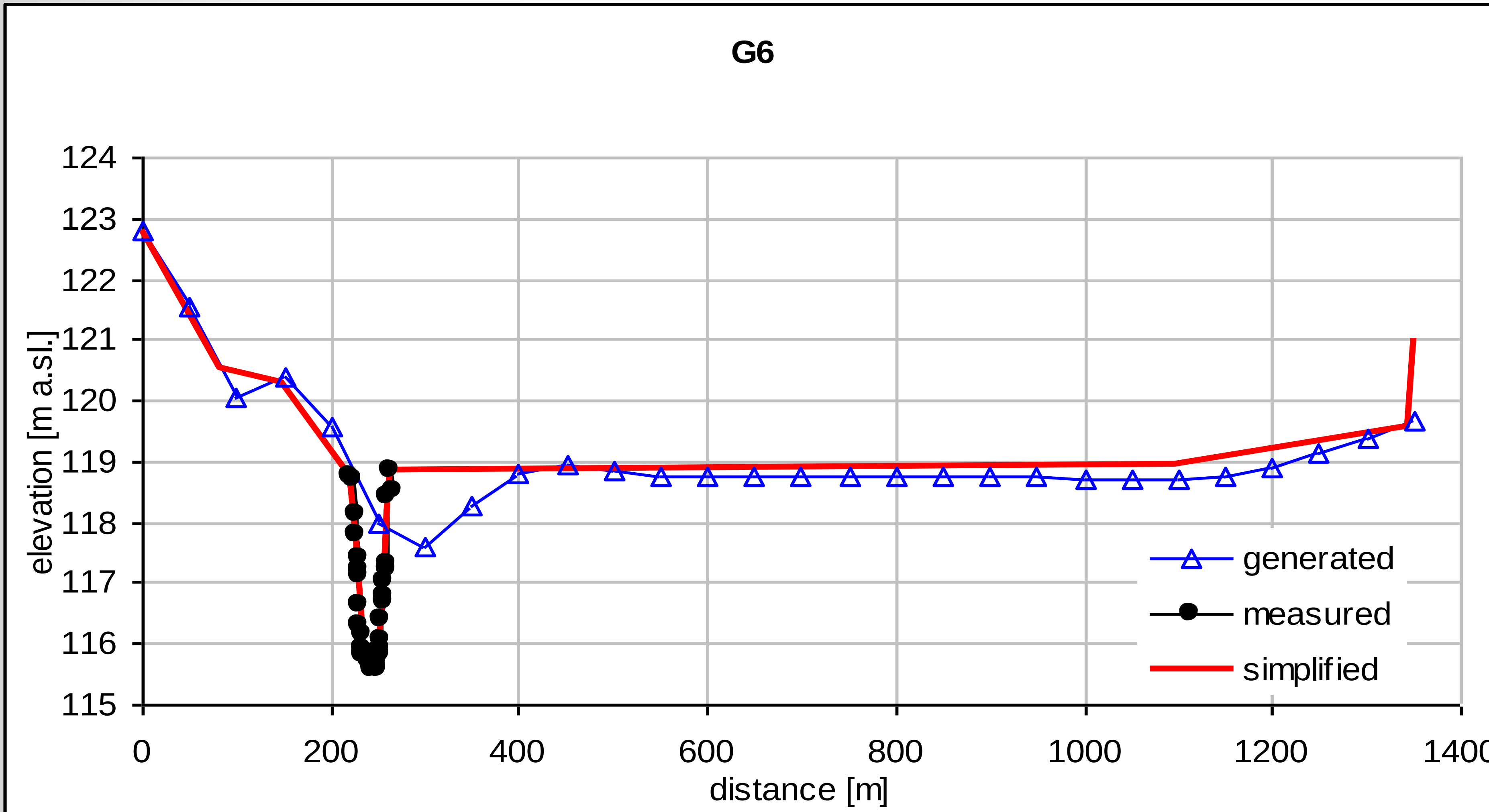
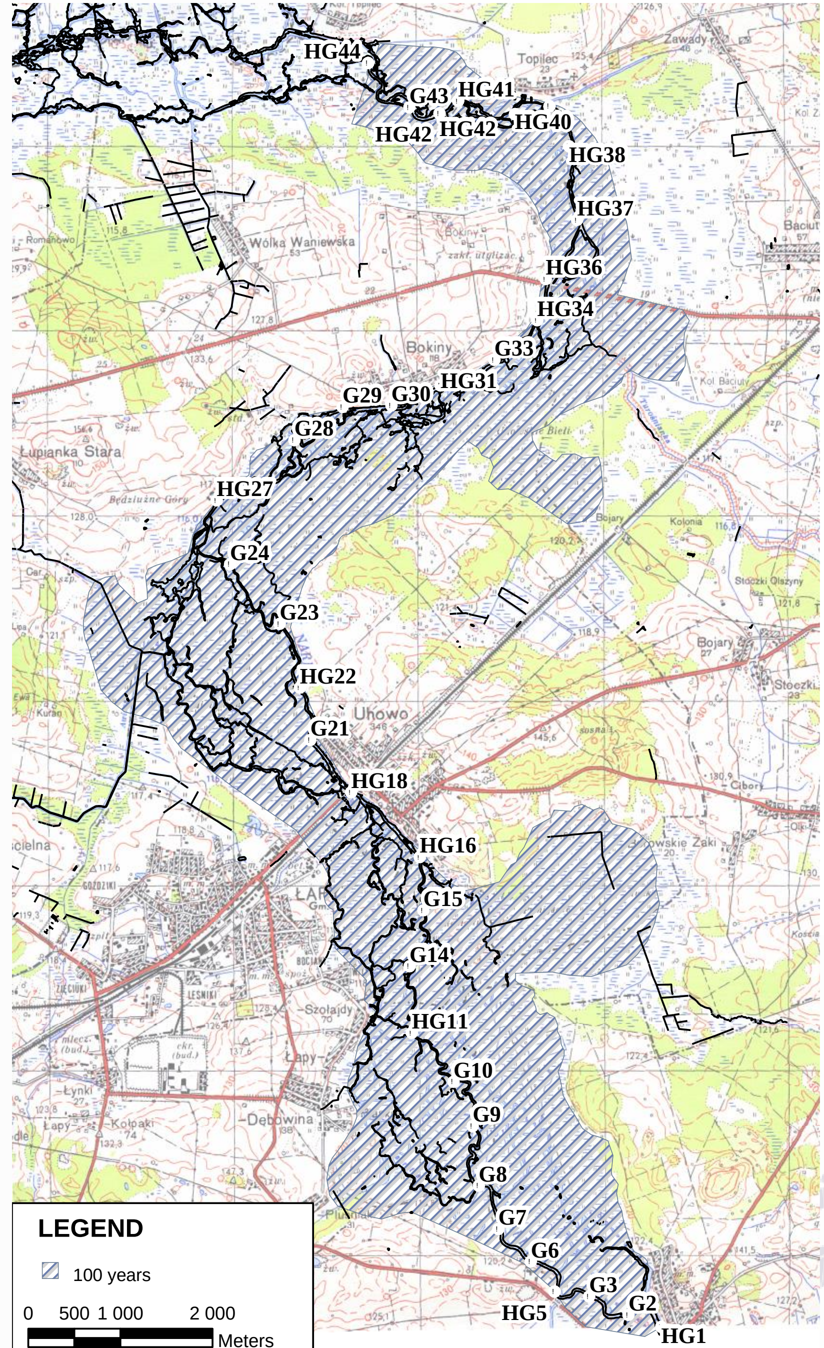
The generated, obtained from a field survey, and simplified selected cross-section – Upper Narew River



Flood area map for the return period of 100 years

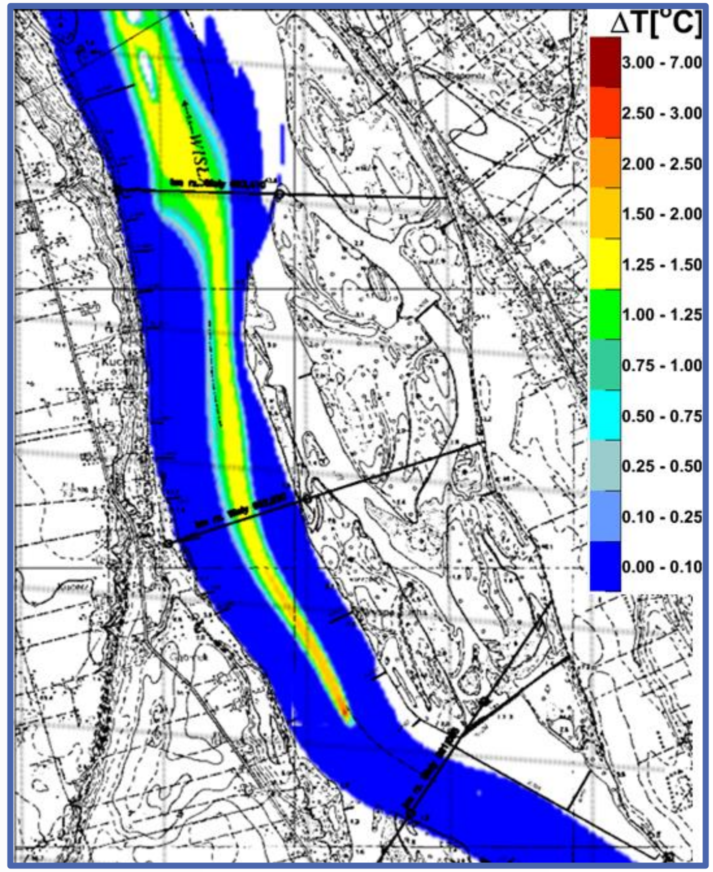
Having identified initial problems can we be totally confident about model results?



Zagadnienie transportu ciepła/masy

Introduction

- **Thermal pollution** is a result of any process that changes ambient water temperature
- In rivers one of the most common reasons for thermal pollution are discharges of heated water from all kinds of industrial facilities (mostly power plants)
- Relatively small changes in natural temperature might create substantial environmental problems
- Construction of e.g. thermal power plants requires the prediction of a possible increase in the water temperature



Predicted thermal plume at power station outfall near Warsaw in Poland (River Vistula)

Rainbow trout, a spiece sensitive to water temperature change. Source: Ken Hammond, USDA

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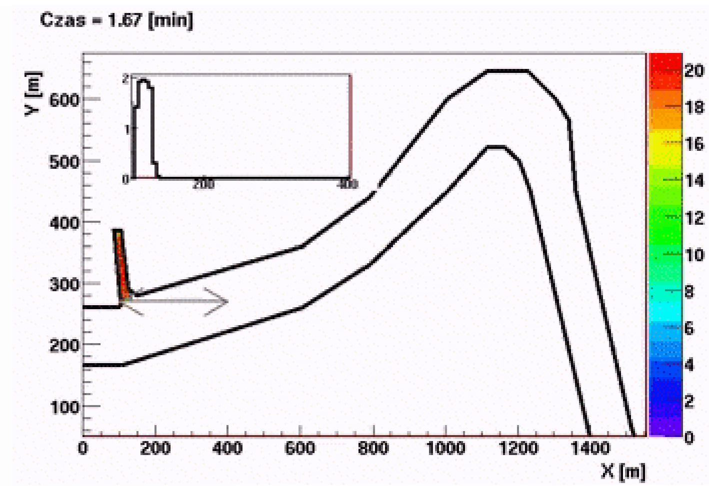
Motivation

RivMix

- **RivMix (River Mixing Model)**
  2D numerical model of the spread
  of passive pollutants
  in flowing surface water
  - Solving the 2D advection-diffusion equation with the included off-diagonal dispersion coefficients



- Which of additional sources associated with the heat exchange with the surrounding environment are significant?
- The problem is especially important in practical cases with limited or not ideal data available
- Sources of uncertainty

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Transport of Heat in Rivers

- Most general 3D transport equation:

$$\frac{\partial T}{\partial t} = \nabla\left[\left(\mathbf{D}_{\mathbf{M}} + \mathbf{D}_{\mathbf{T}}\right)\cdot\nabla T\right] - \nabla\left[\mathbf{v}\cdot T\right] + Q$$

  - t – time [s],
  - $T(\mathbf{x}, t)$ – time-averaged water temperature [°C],
  - $\mathbf{x} = (x, y, z)$ – position vector [m],
  - $\mathbf{v}(\mathbf{x}) = (v_x, v_y, v_z)$ – time-averaged velocity vector [m/s],
  - $\mathbf{D}_{\mathbf{M}}(\mathbf{x})$ – molecular heat diffusion tensor [m^2/s],
  - $\mathbf{D}_{\mathbf{T}}(\mathbf{x})$ – turbulent heat diffusion tensor [m^2/s],
  - Q – source function describing additional heating or cooling processes.

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Transport of Heat in Rivers

- 3D transport equation:

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To solve the 3D transport equation a huge amount of information is required

All that data are usually difficult to obtain

The computational costs of the solution of such equation are also very high

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Transport of Heat in Rivers

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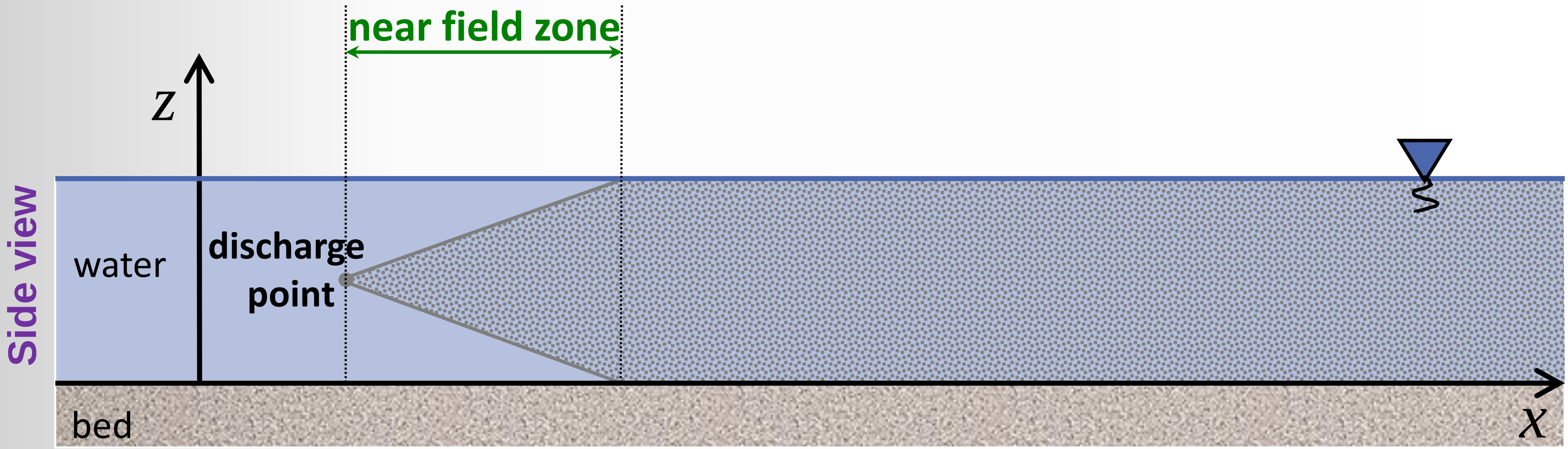
Different simplifications are considered in practice

The most obvious simplifications pertain to the reduction of the problem to 2D or even 1D

Mixing zones in river

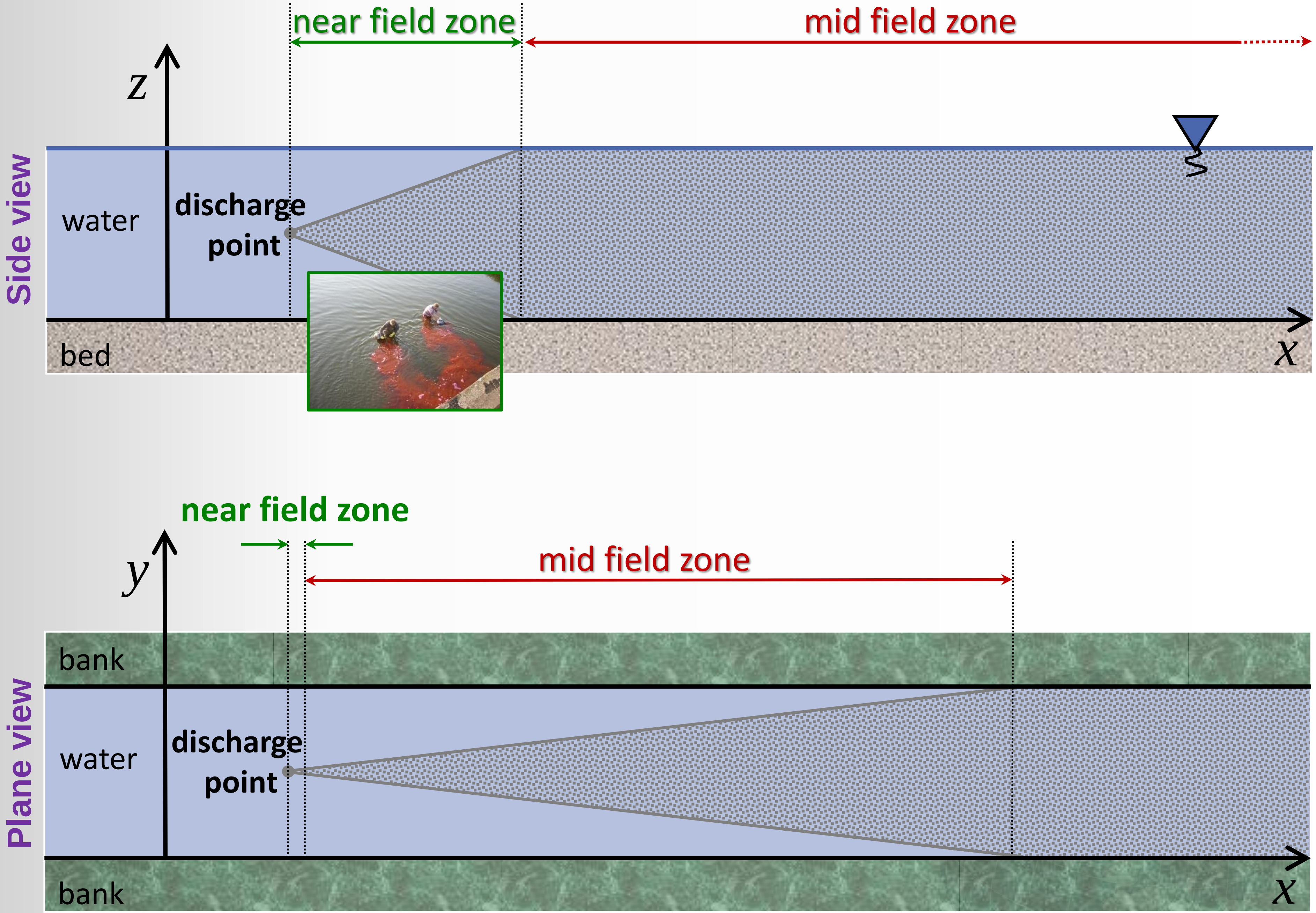


Near field zone

- Vertical mixing prevails

Tracer test performed in a natural Narew River in the North-East of Poland, June 2005

starting at the discharge point
and continuing to the point of complete vertical mixing



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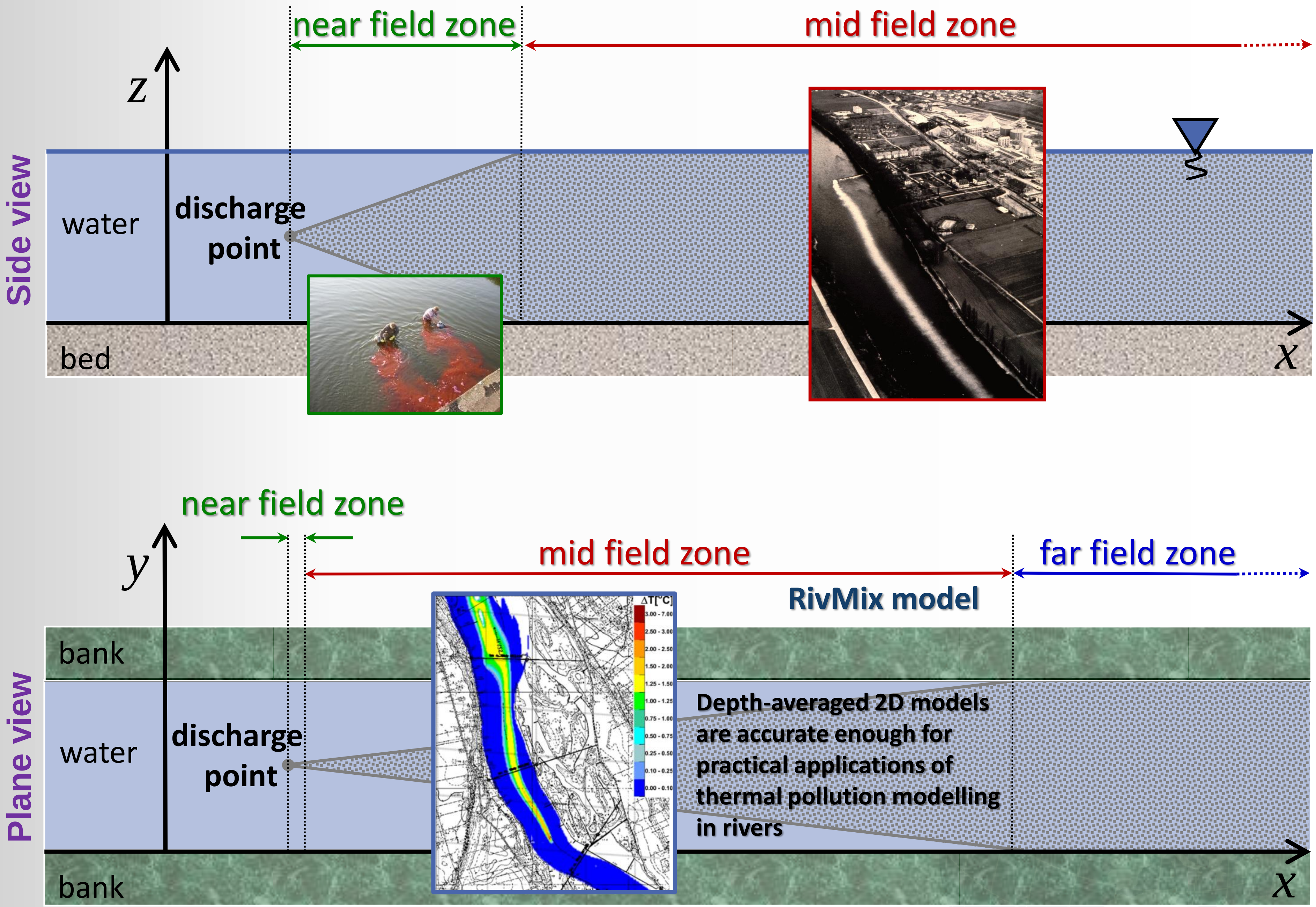
Mid field zone

- May continue for a very long distance, horizontal mixing prevails

Tracer study in Missouri River, source: Holley, 2001

River Rhine – industrial discharge source: Jirka and Weitbrecht, 2005

stretching down the river until complete lateral mixing occurs



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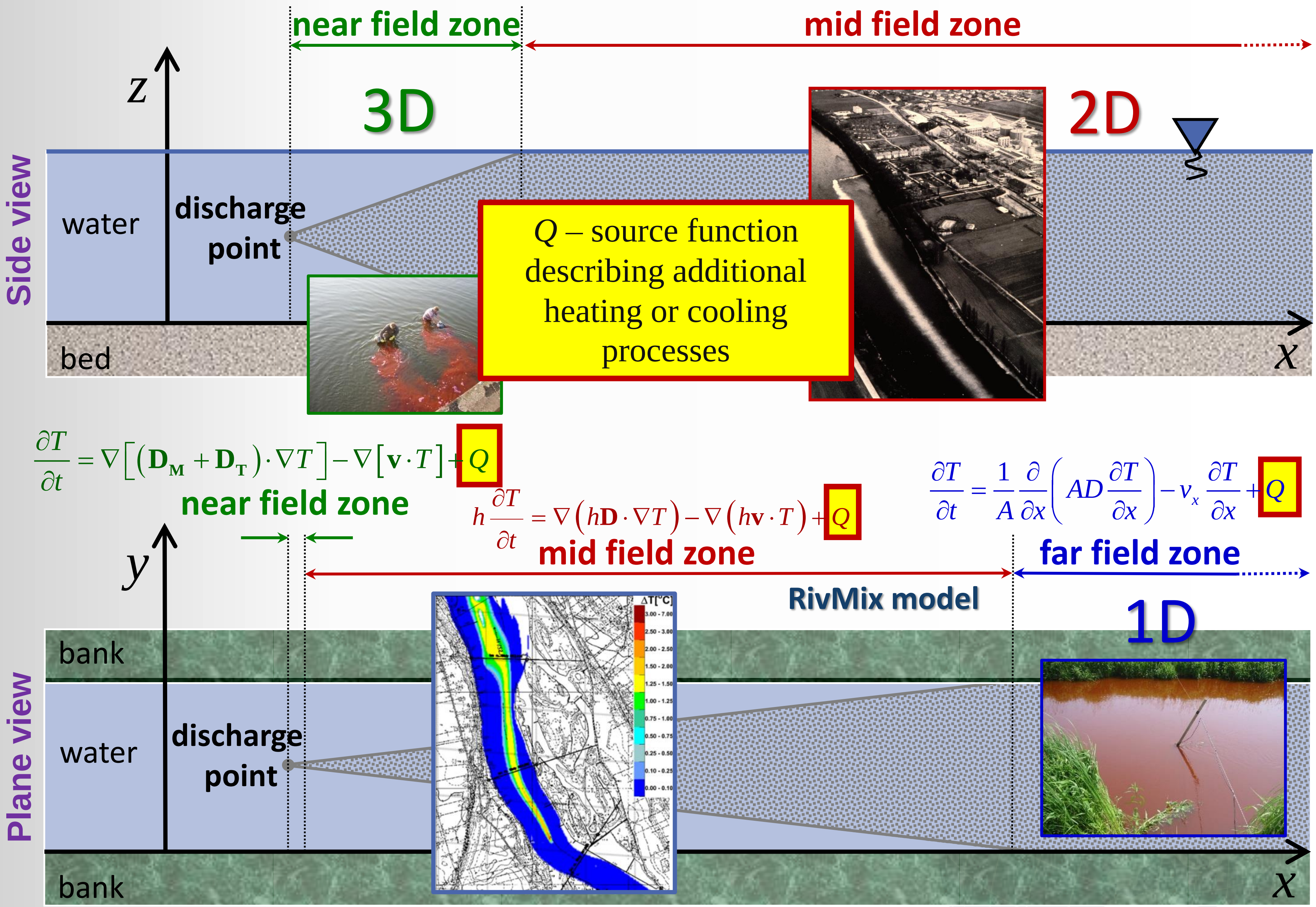
Far field zone

Tracer test performed in a natural Narew River in the North-East of Poland, June 2005;
after complete mixing along the river width

starting after the complete mixing along the depth and width of the channel



See details: Kalinowska M. B., Rowiński, P. M., (2015). Thermal pollution in rivers – modelling of the spread of thermal plumes". *Rivers – physical, fluvial and environmental processes*, Springer

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2D równanie transportu masy

- uśrednione wzdłuż głębokości 2D równanie adwekcji-dyfuzji:

$$h(\mathbf{x})\frac{\partial c(\mathbf{x},t)}{\partial t} = \underbrace{\nabla\left(h(\mathbf{x})\mathbf{D}(\mathbf{x})\cdot\nabla c(\mathbf{x},t)\right)}_{\text{człon dyfuzyjny}} - \underbrace{\nabla\left(h(\mathbf{x})\mathbf{v}(\mathbf{x})\cdot c(\mathbf{x},t)\right)}_{\text{człon adwekcyjny}}$$

t – czas

$\mathbf{x} = (x, y)$ – współrzędne położenia

$\mathrm{c}(\mathbf{x},t)$ – stężenie (koncentracja)

$\mathbf{v}(\mathbf{x})$ – pole prędkości

h – lokalna głębokość

$\mathbf{D} = (\mathbf{x})$ – tensor dyspersji

$$\mathbf{D} = \begin{bmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{bmatrix}$$

Współczynniki dyspersji w układzie kartezjańskim tworzą niediagonalny tensor

2D równanie transportu masy

$$\mathbf{D} = \begin{bmatrix} D_{xx} & \cancel{D_{xy}} \\ \cancel{D_{yx}} & D_{yy} \end{bmatrix}$$

✓ **Jakiekolwiek uproszczenia prowadzące do pominięcia pozadiagonalnych składowych tensora wprowadzają błąd**

2D równanie transportu masy

Skupia wszystkie problemy modelowania hydrodynamicznego:

- określenie pola prędkości
- geometria
- dane wejściowe
- weryfikacja
- metody numeryczne

Uproszczenia

- **Quasi obrót**
- **Przekształcenie tożsamościowe**
- **Obrót wektora**

Uproszczenia

$$D = D_L - D_T, \quad v = \sqrt{v_x^2 + v_y^2}$$

Quasi obrót

Pominięcie pozadiagonalnych składowych tensora dyspersji;
D_{xy} i D_{yx} arbitralnie równe 0

$$\mathbf{D} = \begin{bmatrix} D_{xx} & \cancel{D_{xy}} \\ \cancel{D_{yx}} & D_{yy} \end{bmatrix}$$

$$D_{xx} = D_T + D\frac{v_x^2}{v^2};$$

$$D_{xy} = D_{yx} = 0;$$

$$D_{yy} = D_T + D\frac{v_y^2}{v^2};$$

Przekształcenie tożsamościowe

Tensor nie jest wcale przekształcony
$D_{xx} = D_L$, $D_{yy} = D_T$

$$\mathbf{D} = \begin{bmatrix} D_L & 0 \\ 0 & D_T \end{bmatrix}$$

$$D_{xx} = D_L;$$

$$D_{xy} = D_{yx} = 0;$$

$$D_{yy} = D_T;$$

Obrót wektora

Potraktowanie diagonalnych współczynników jako wektor

$$\mathbf{D}_D = [D_L, D_T]$$

obrót

$$\mathbf{D} = [D_{xx}, D_{yy}]$$

$$D_{xx} = \left| D_L \frac{v_x}{v} + D_T \frac{v_y}{v} \right|;$$

$$D_{xy} = D_{yx} = 0;$$

$$D_{yy} = \left| D_L \frac{v_y}{v} + D_T \frac{v_x}{v} \right|;$$

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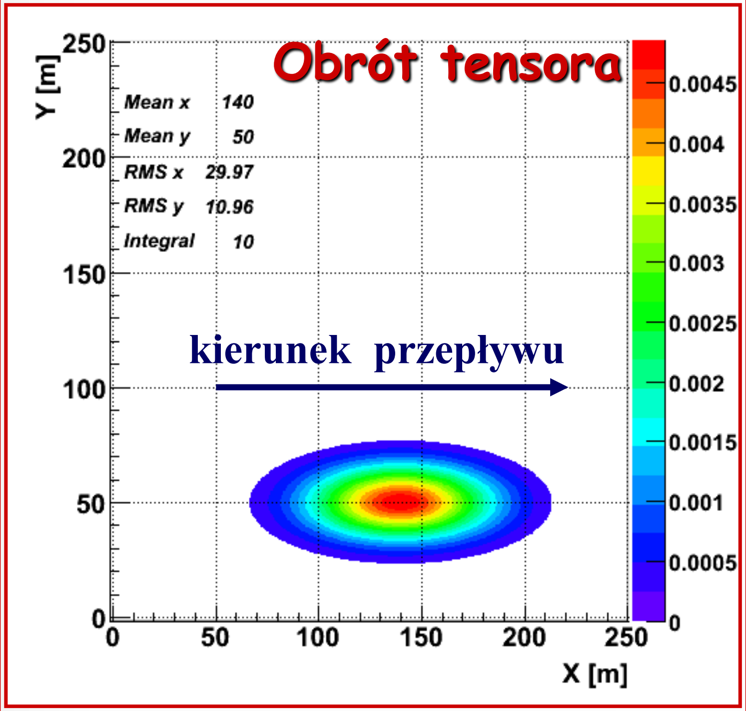
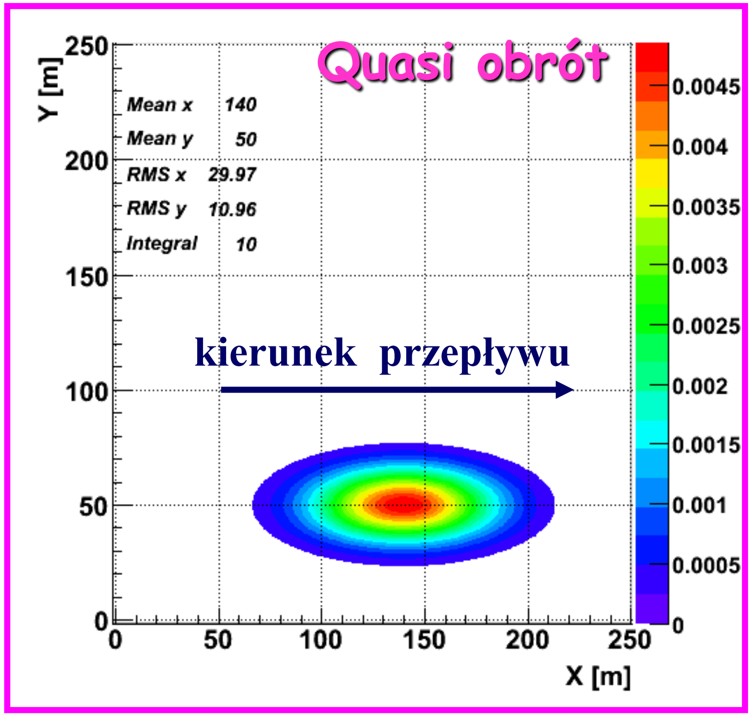
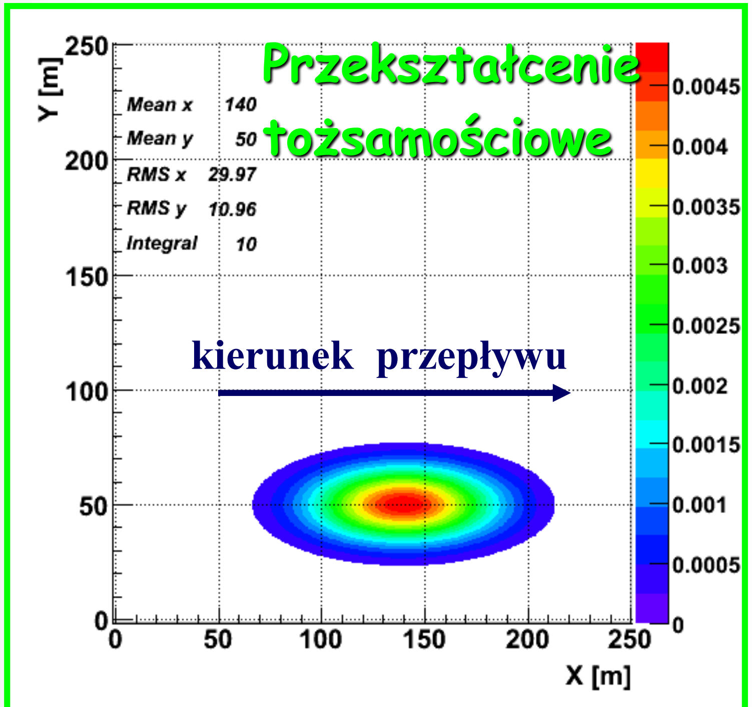
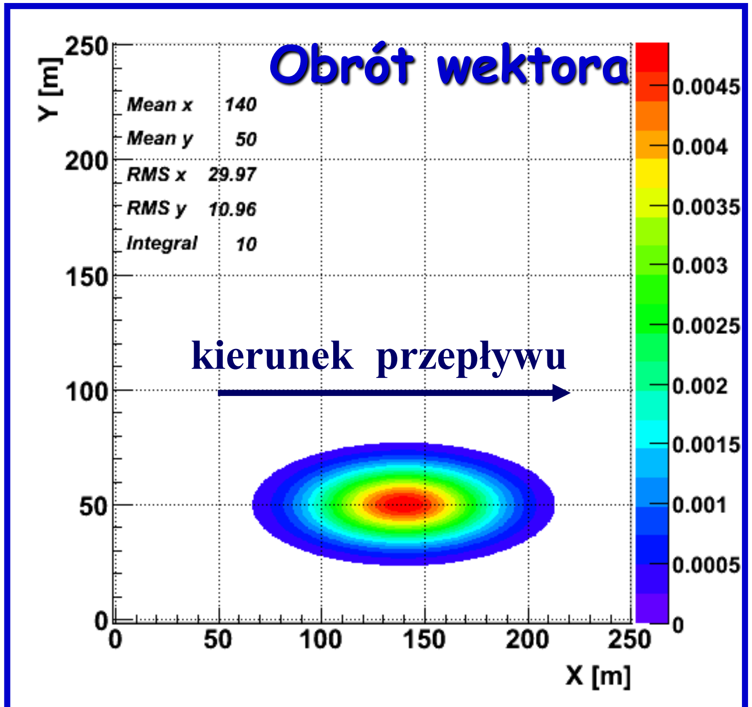
Chwilowy zrzut substancji rozpuszczonej

$\alpha = 0^{o}$



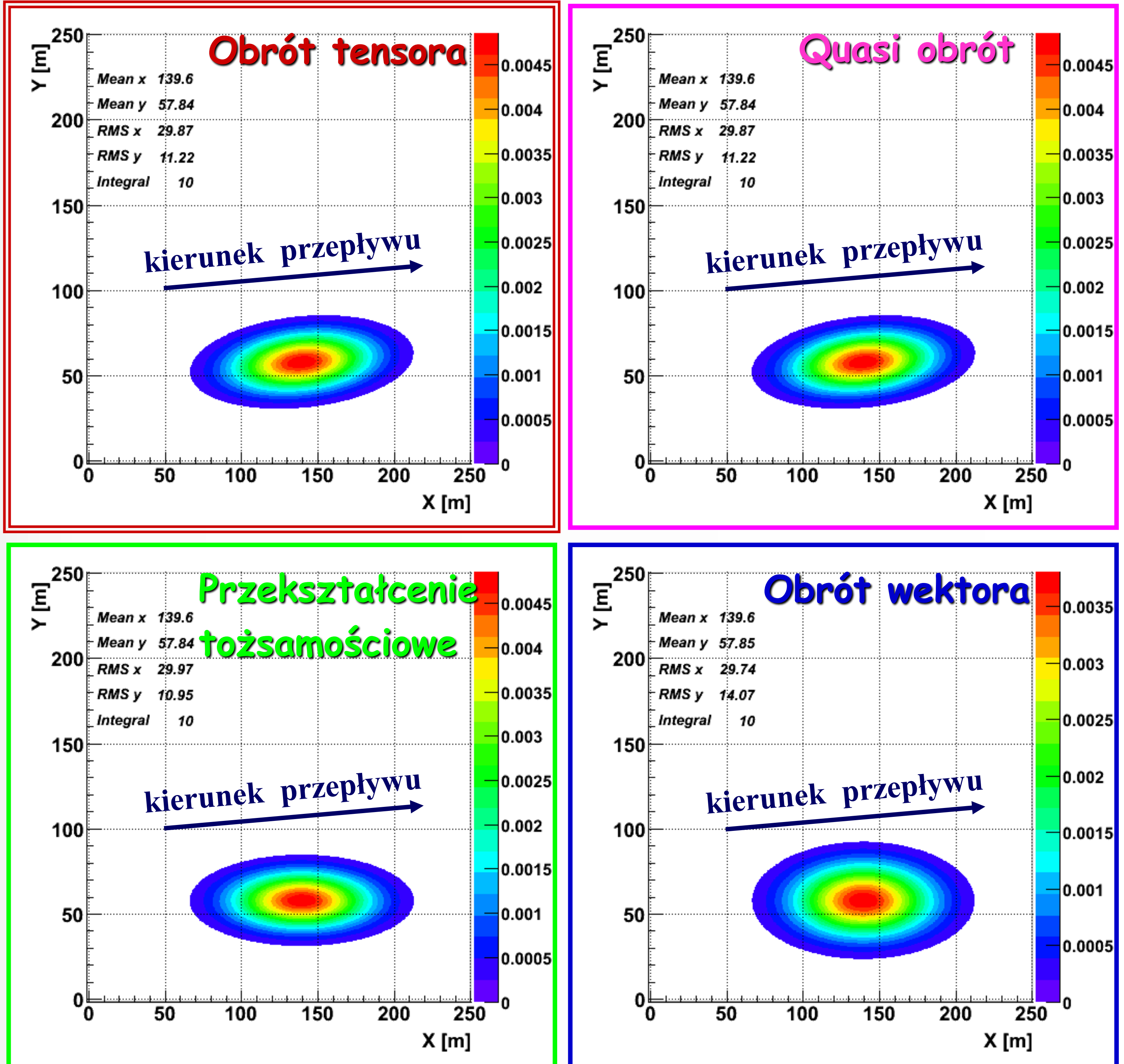






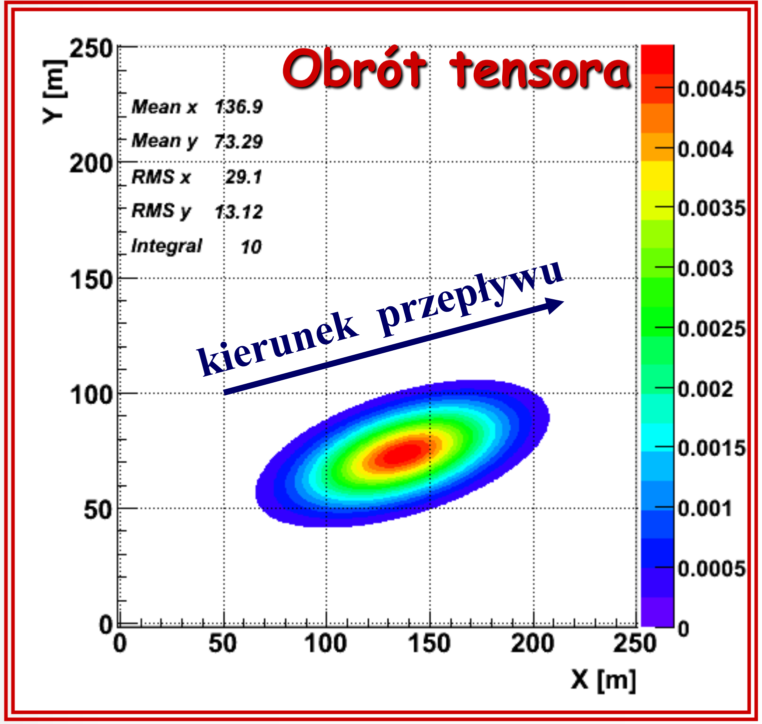
$\alpha = 5^{o}$

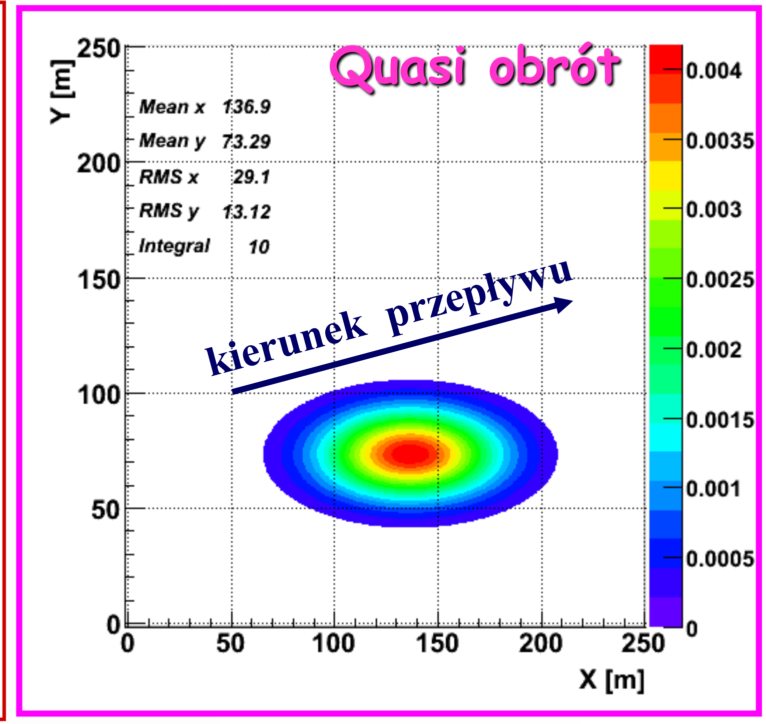
Chwilowy zrzut substancji rozpuszczonej

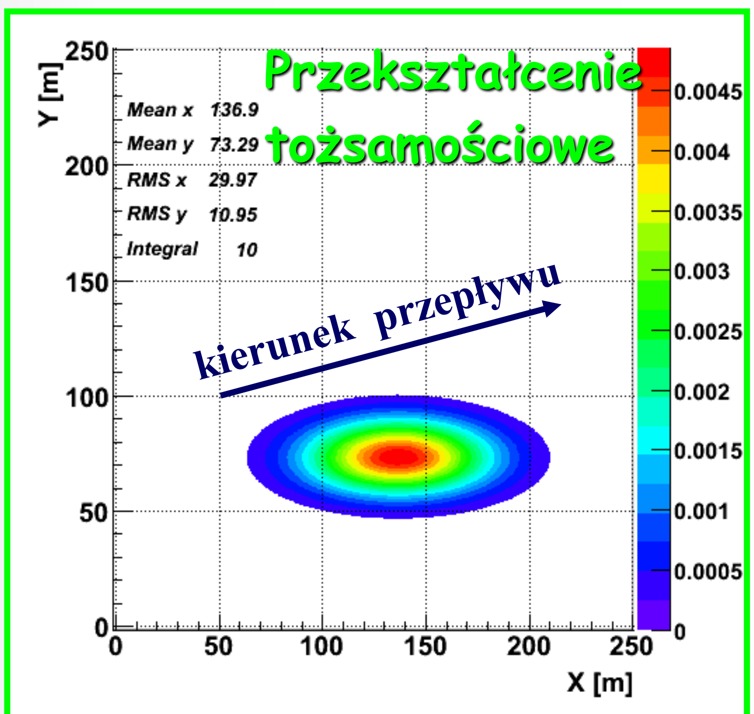


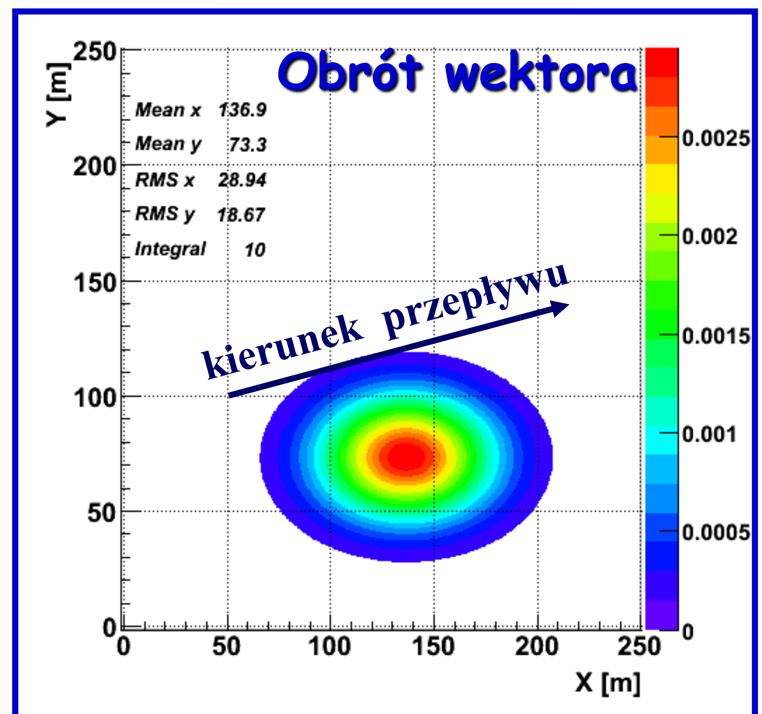
$\alpha = 15^{o}$

Chwilowy zrzut substancji rozpuszczonej



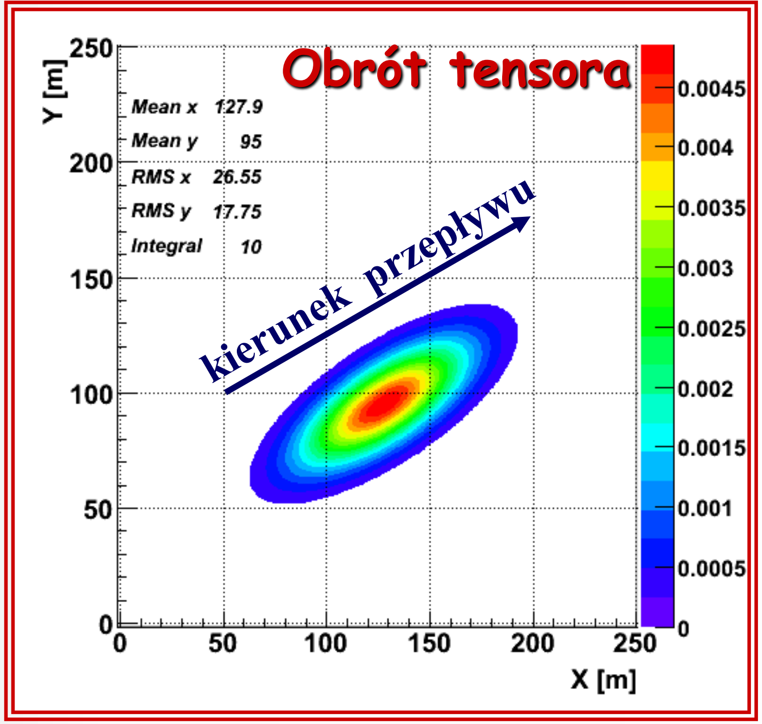


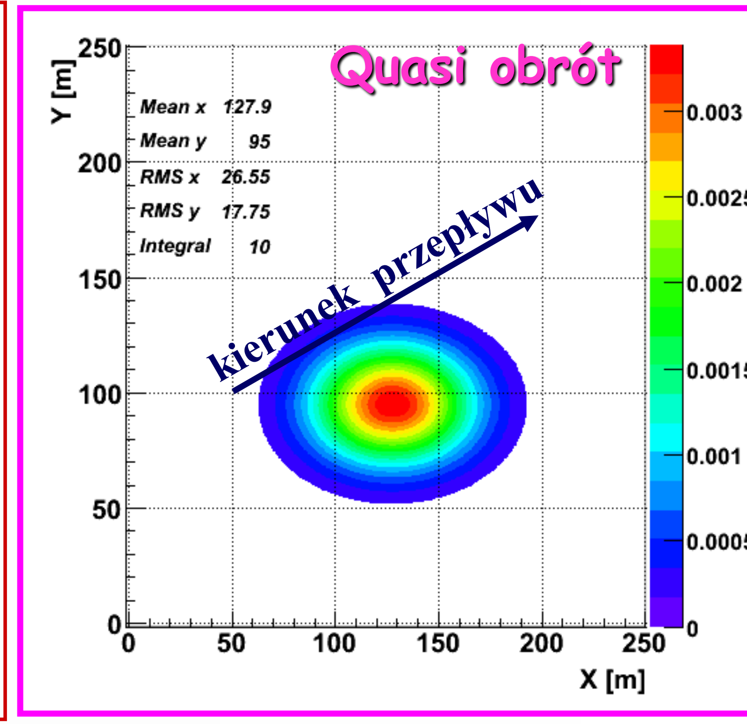


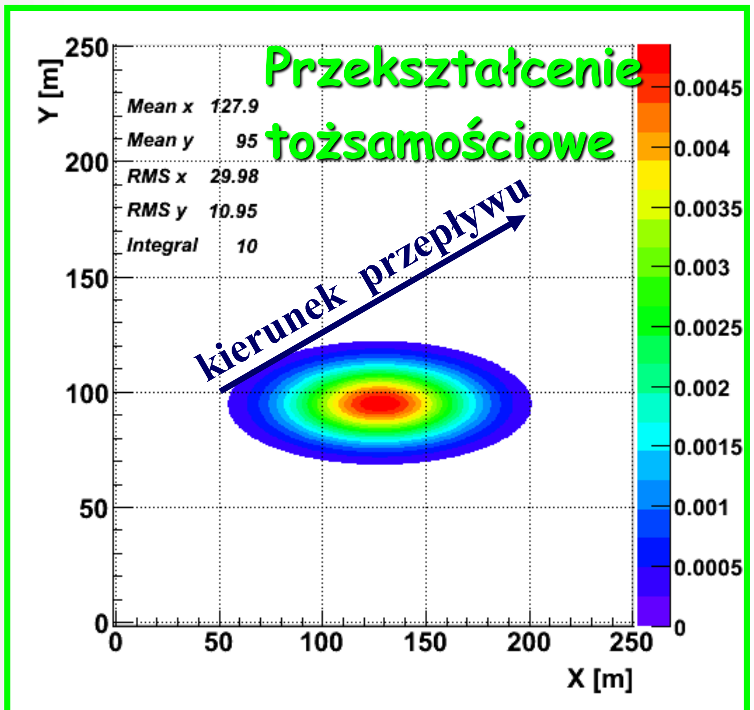


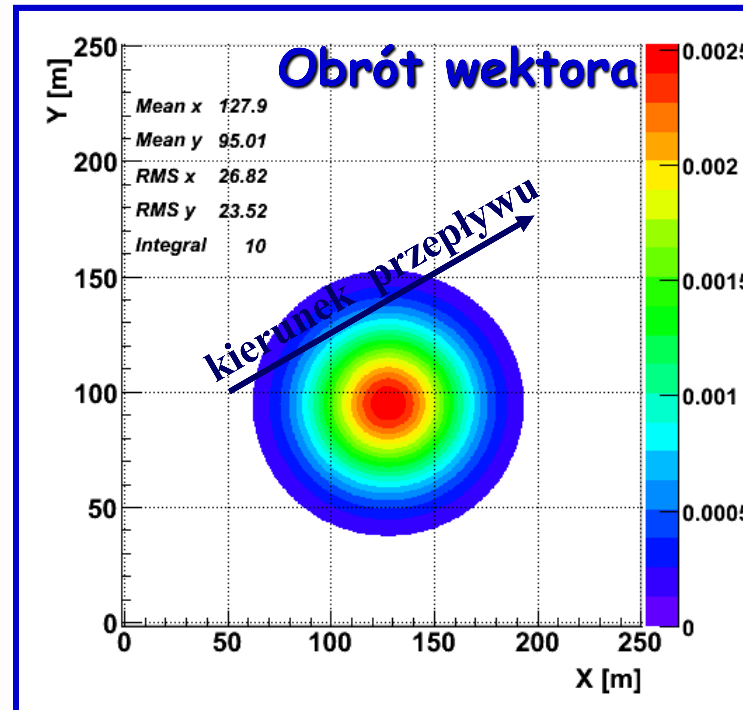
α = 30°

Chwilowy zrzut substancji rozpuszczonej



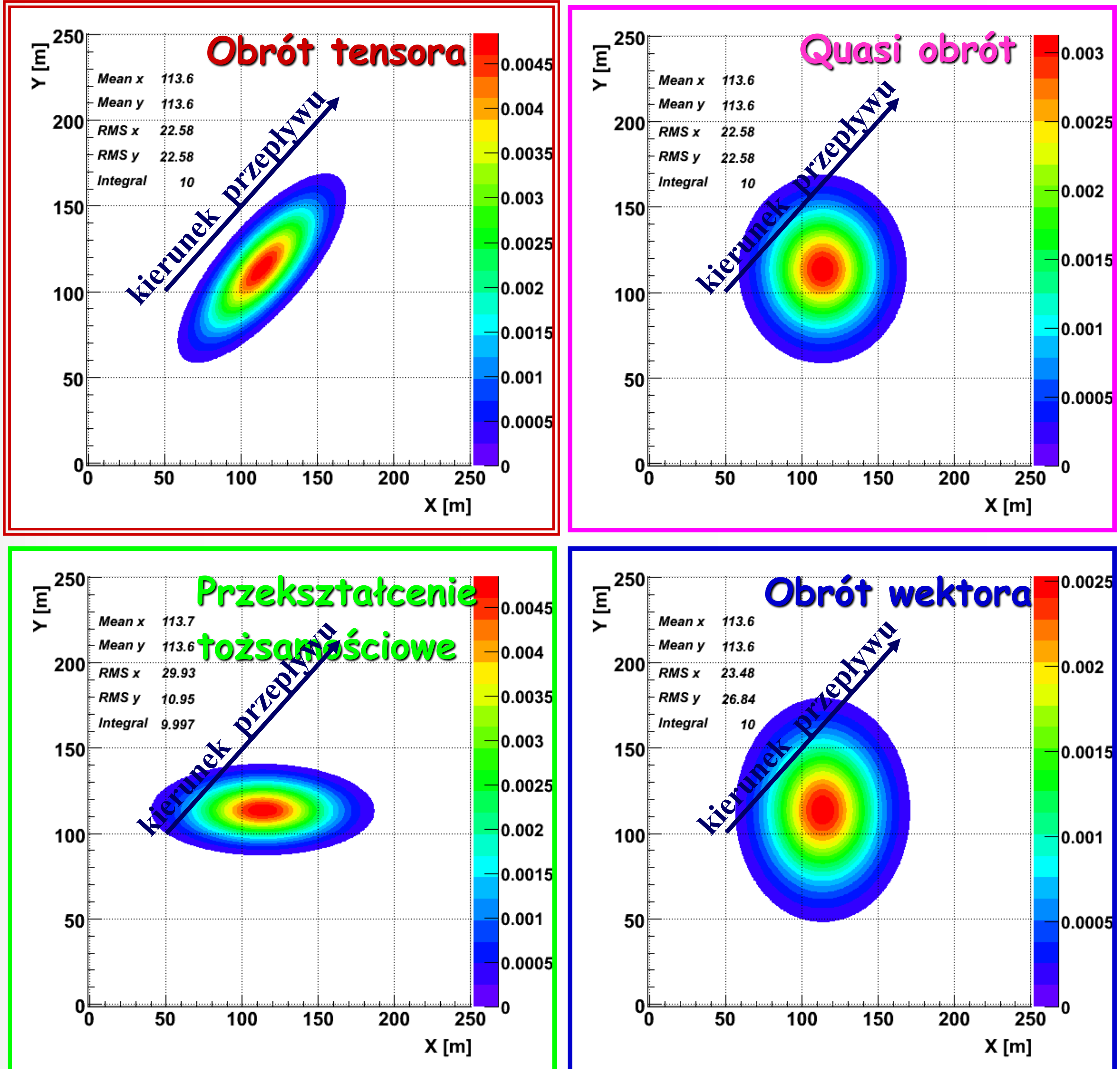






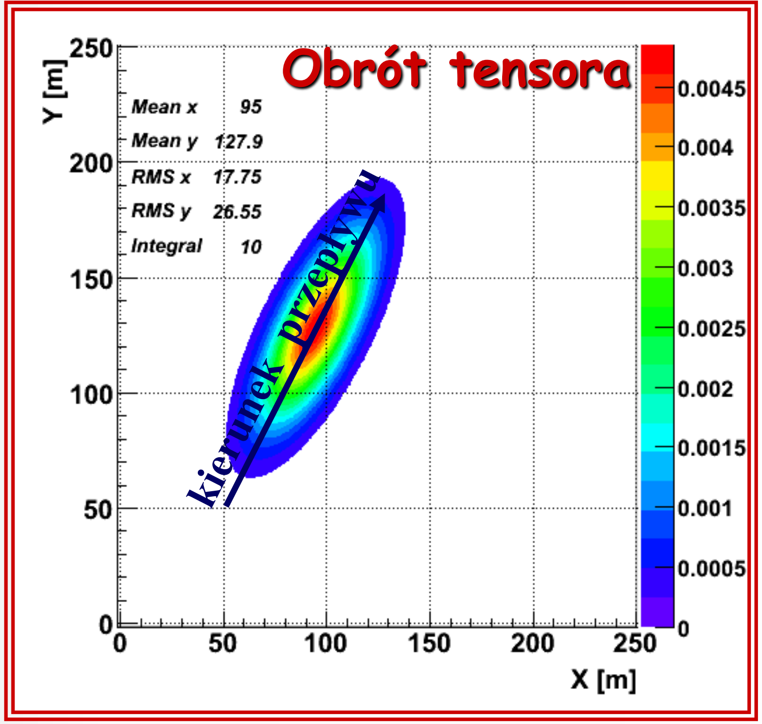
$\alpha = 45^{o}$

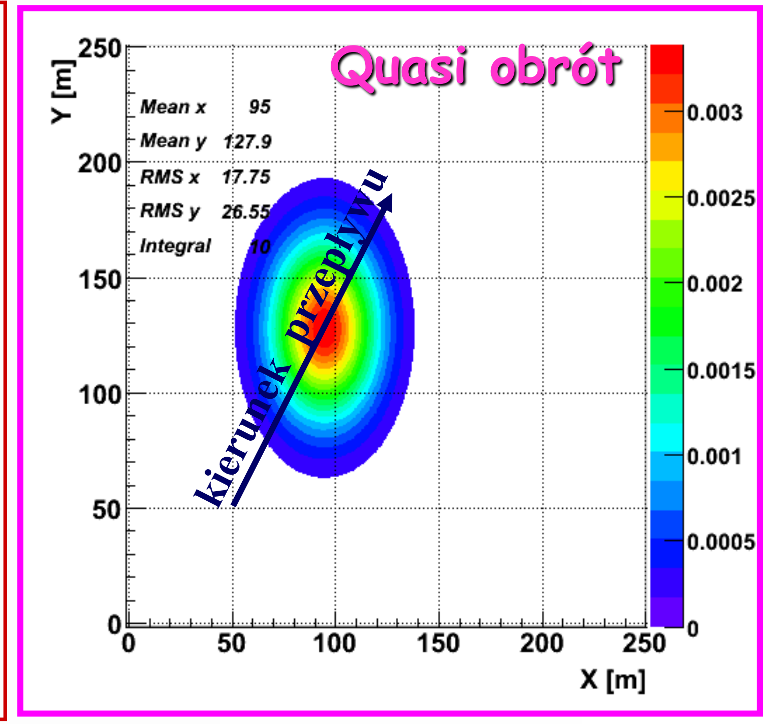
Chwilowy zrzut substancji rozpuszczonej

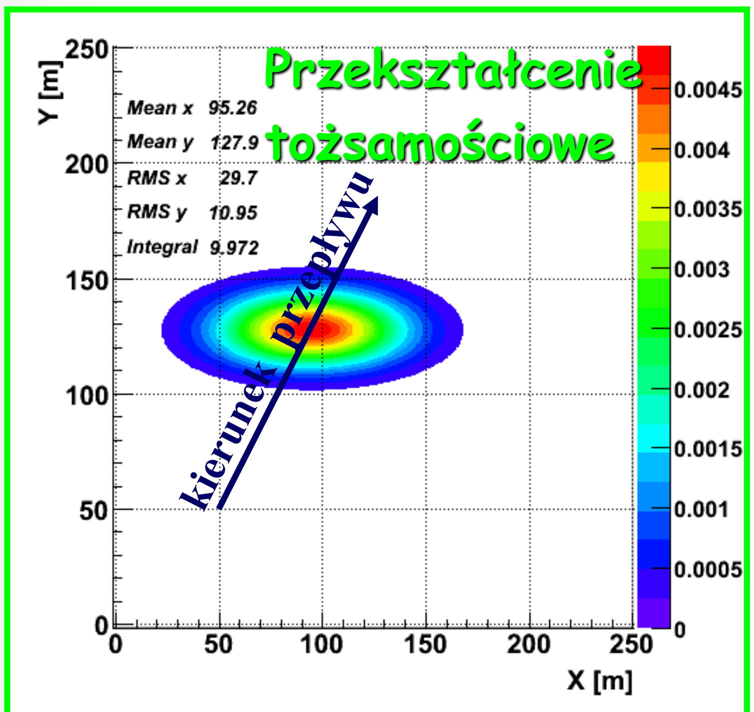


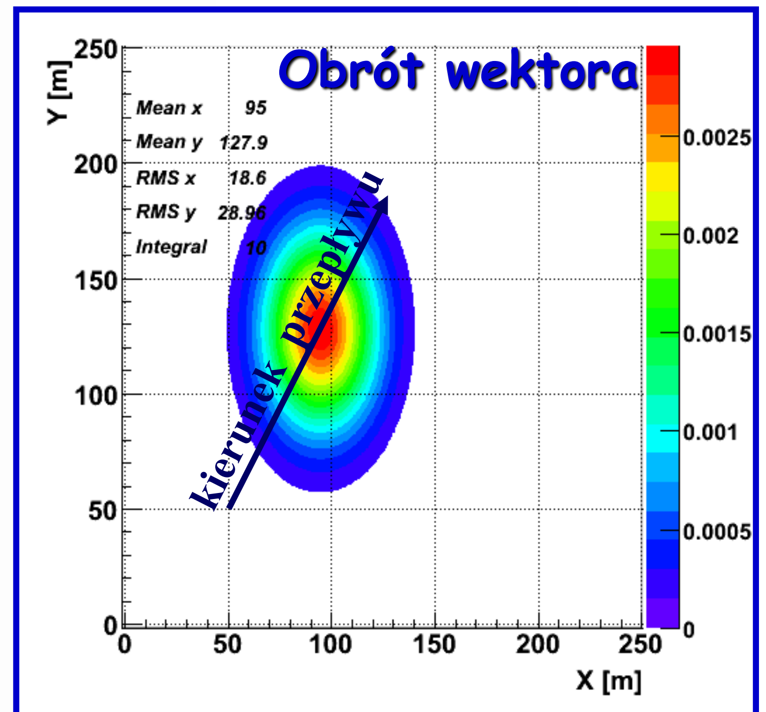
α = 60°

Chwilowy zrzut substancji rozpuszczonej

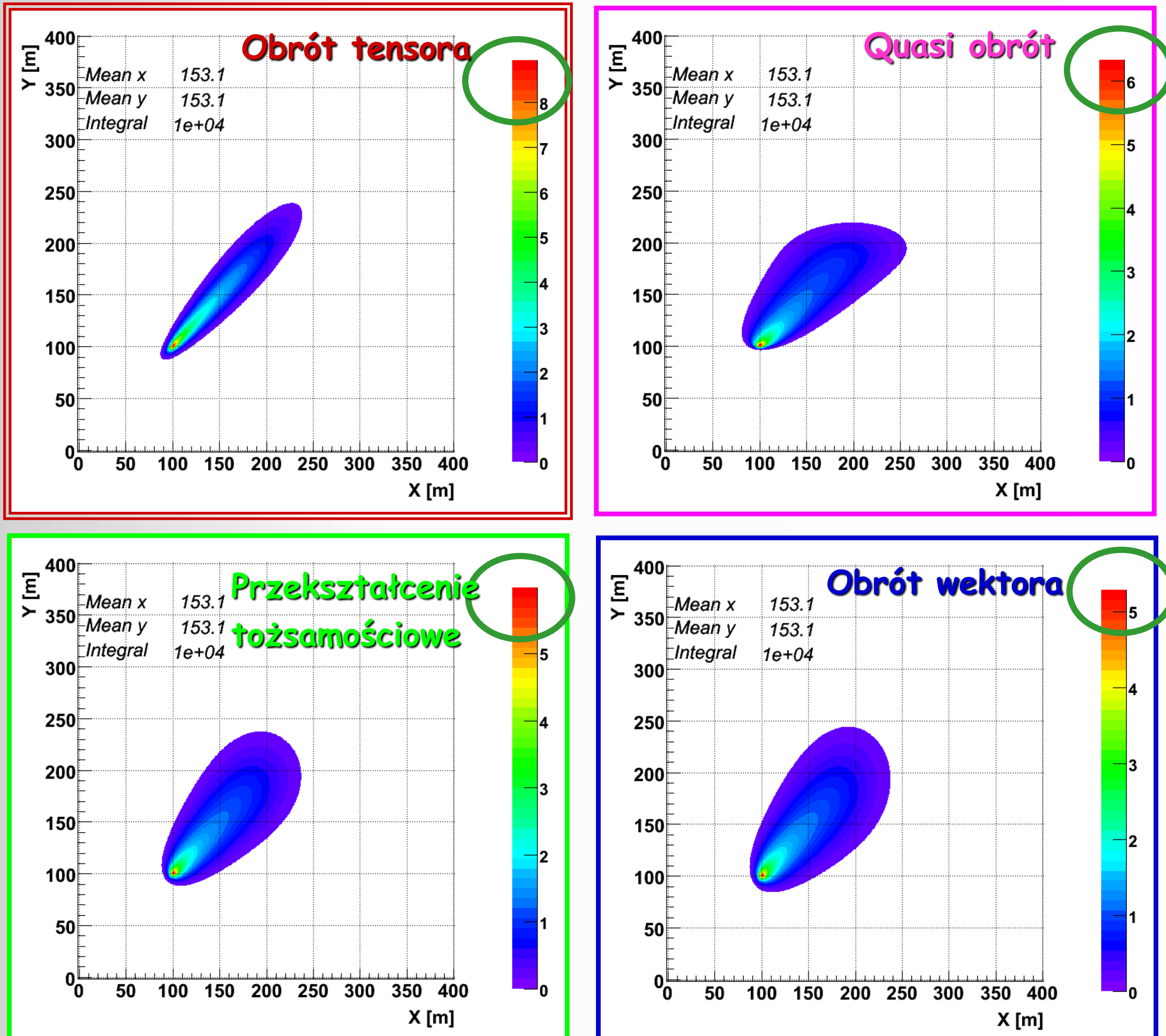








Ciągły zrzut substancji rozpuszczonej



$\alpha = 45^o$

Informacja na temat maksymalnej wartości stężenia może być błędna

Przykłady obliczeniowe

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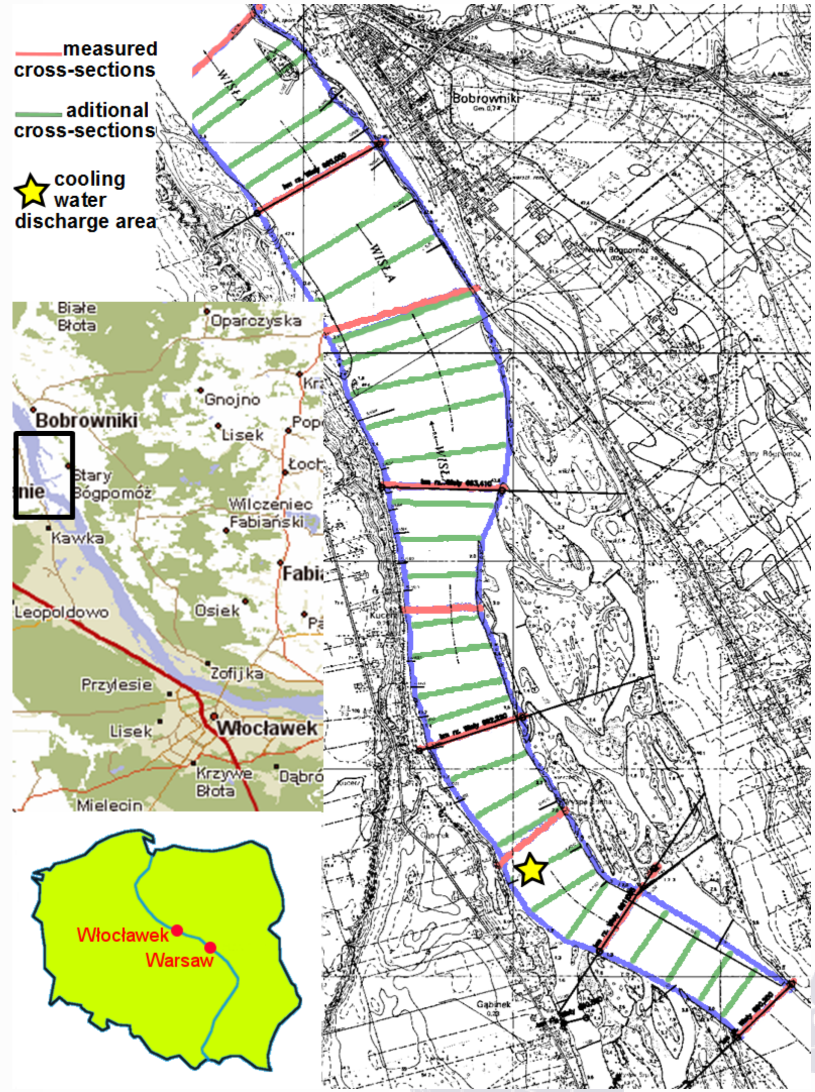
Pierwszy przykład obliczeniowy

- The computations have been done for the mean low-flows of the river Q = 334 m^3/s
- All results have been prepared using:
  - **RivMix** (temperature field) model
    - River Mixing Model, developed in Institute of Geophysics Polish Academy of Sciences is the 2D numerical model of the spread of passive pollutants in flowing surface water, solving the 2D advection-diffusion equation with the included off-diagonal dispersion coefficients
  - **CCHE2D** (velocity field) model
    - Developed by NCCHE – National Center for Computational Hydroscience and Engineering is the 2D depth-averaged, unsteady turbulent open channel flow model. The model is based on the depth-averaged Navier-Stokes equations.
  - **ROOT** (for visualization)
    - Object Oriented Data Analysis Framework, developed at the European Laboratory for Particle Physics – CERN

(see details: Kalinowska et al, Acta Geophysica 2012)

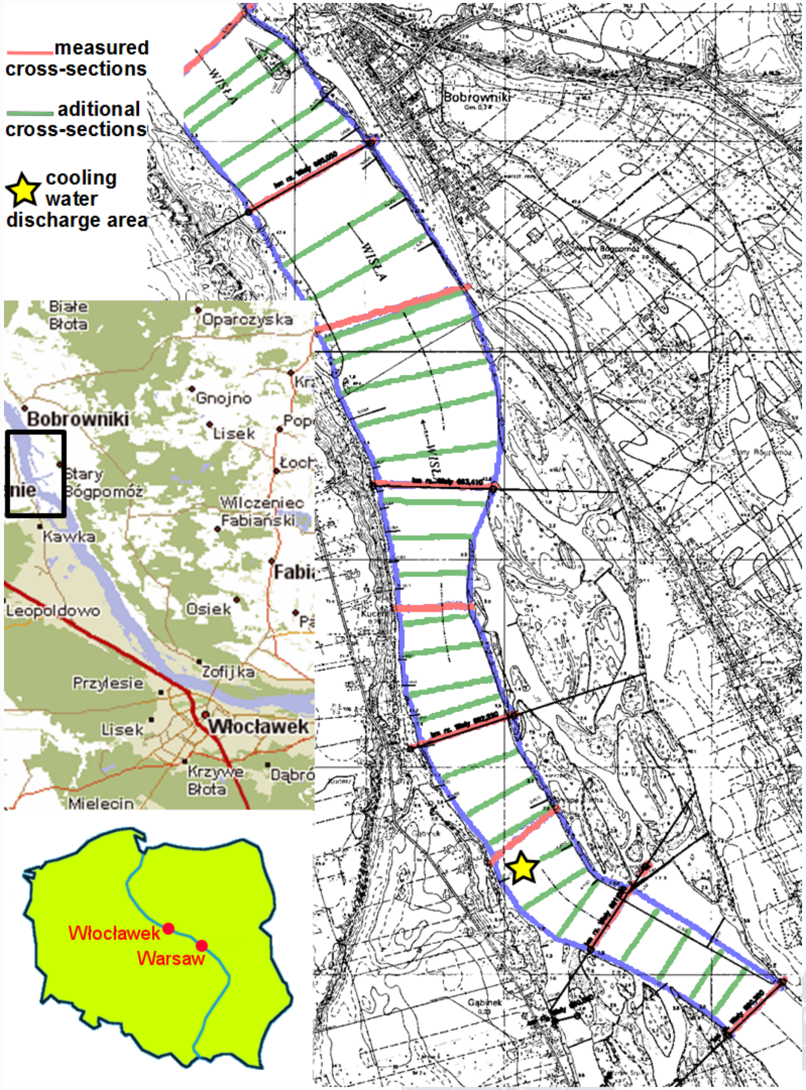
Geometry

- 21 cross-sections of the ca 28 kilometers of Vistula River reach
  - obtained in 1994 with use of electroacoustic probes
- 9 cross-sections were used in the calculations
  - Preliminary computations showed that the considered stretch of the river may be reduced to 4 km



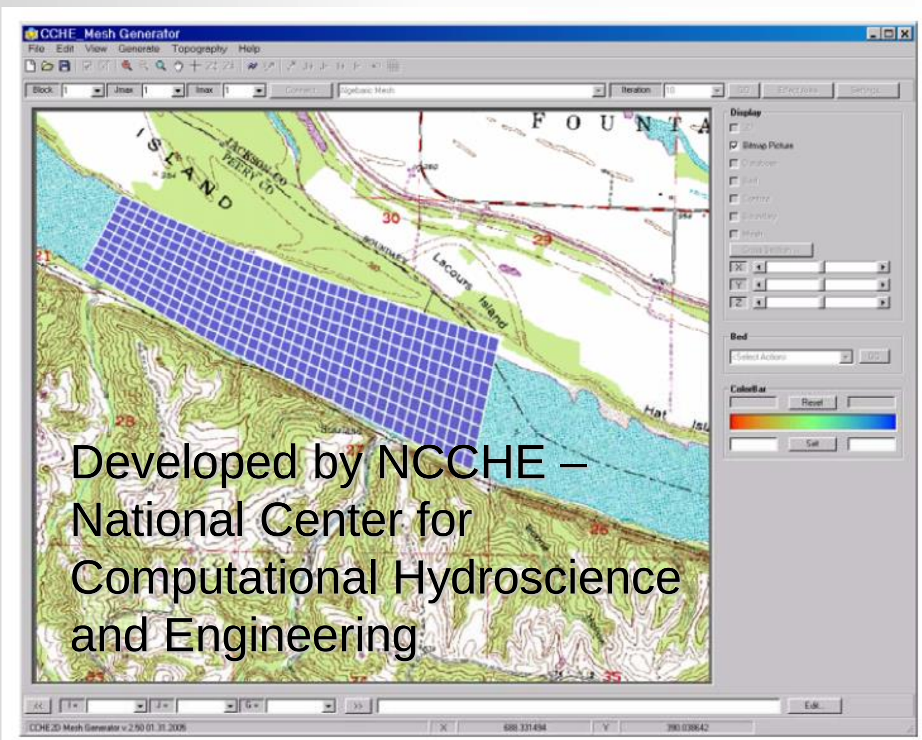
Geometry

- The averaged distance between two consecutive cross-sections is about 1 km
- 26 additional cross-sections (green lines), have been added

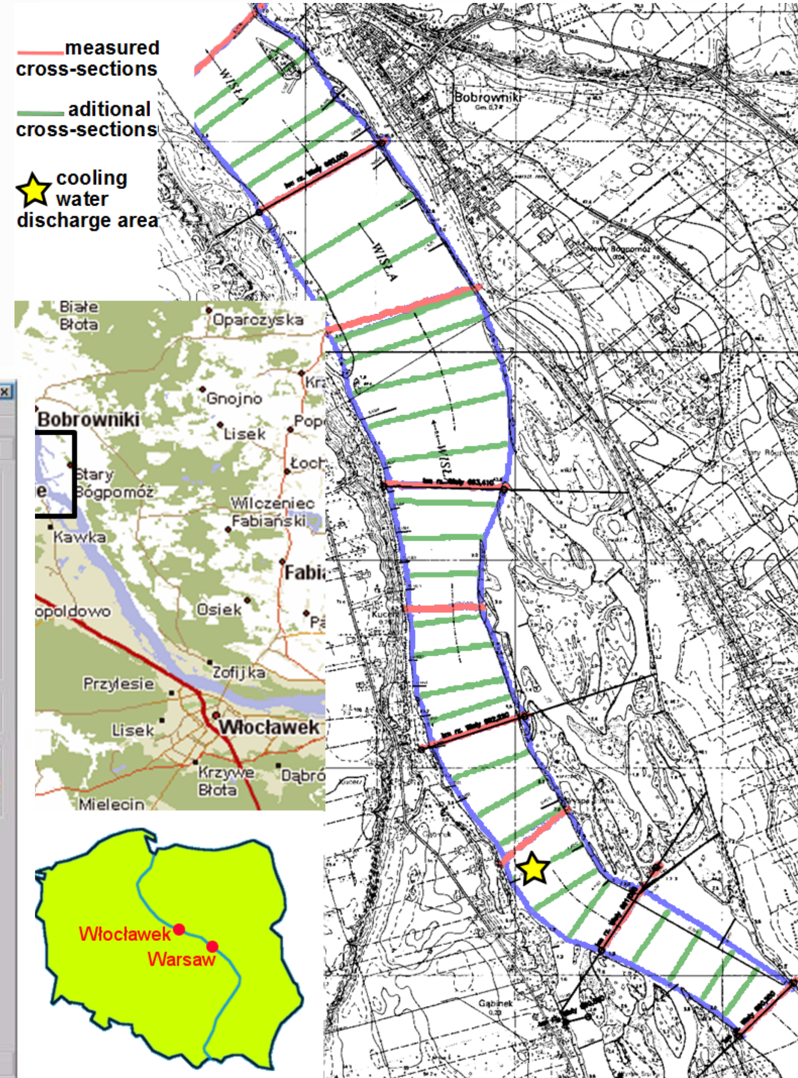


Computational mesh

- 2D computational grid and the bed profile have been prepared using the CCHE_MESH generator



Developed by NCCHE – National Center for Computational Hydroscience and Engineering



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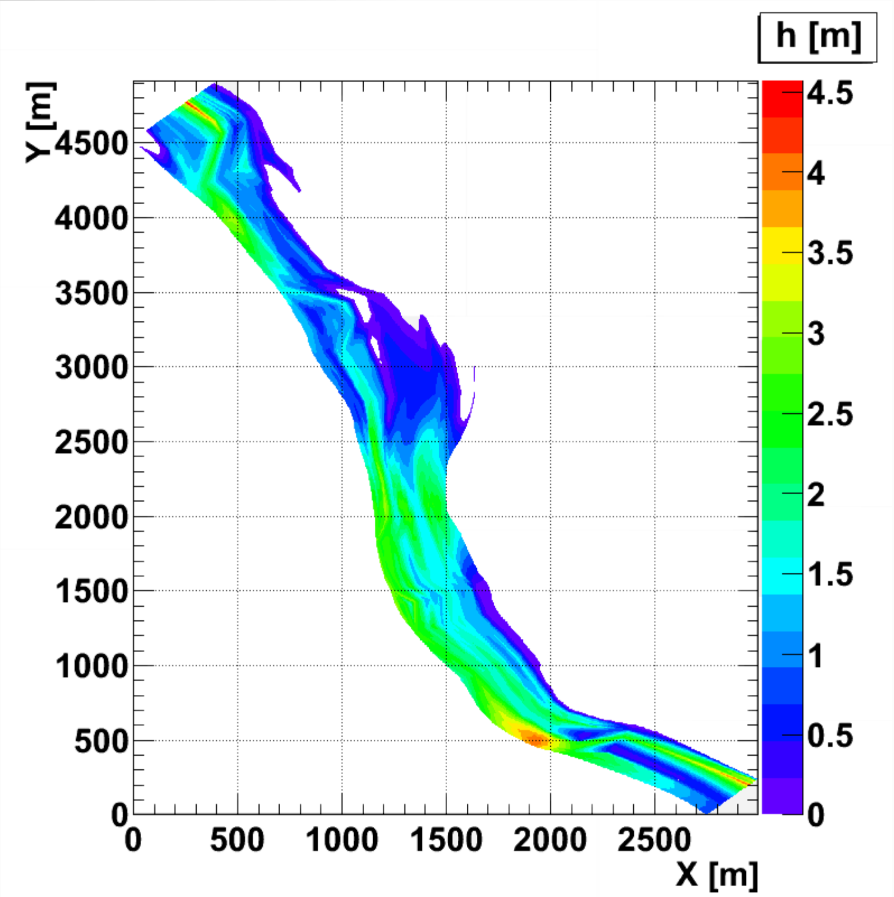
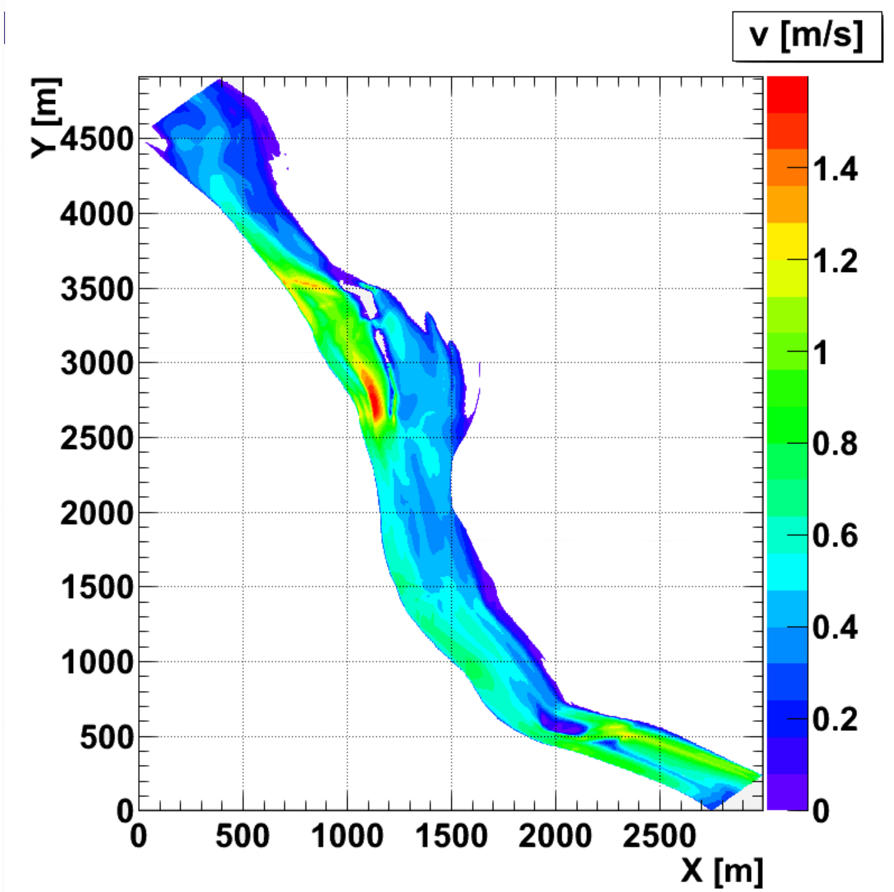
Computations





used as the input to the heat transport model

Uncertainty in computations

- Problems encountered during solving the practical cases:
  - limited data and information
  - measurement errors
  - simplification of transport equation
  - errors introduced by the models used in the calculation, numerical errors
  - geometry
    - insufficient number of the measured cross-sections
    - interpolation procedures
  - setting the initial and boundary conditions
  - determination of coefficients
    - dispersion coefficients

(see details: Kalinowska & Rowiński, HESSD 2012)

Determination of dispersion coefficients

- Dispersion coefficients are essential for the solution of the transport equation
  - controlling the rate of mixing
  - the most important and the most difficult to determine factors

- In general case in Cartesian coordinates the dispersion coefficients form a non-diagonal dispersion tensor:

$$\mathbf{D} = \begin{bmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{bmatrix}$$

D_L longitudinal dispersion coefficient

D_T transverse dispersion coefficient

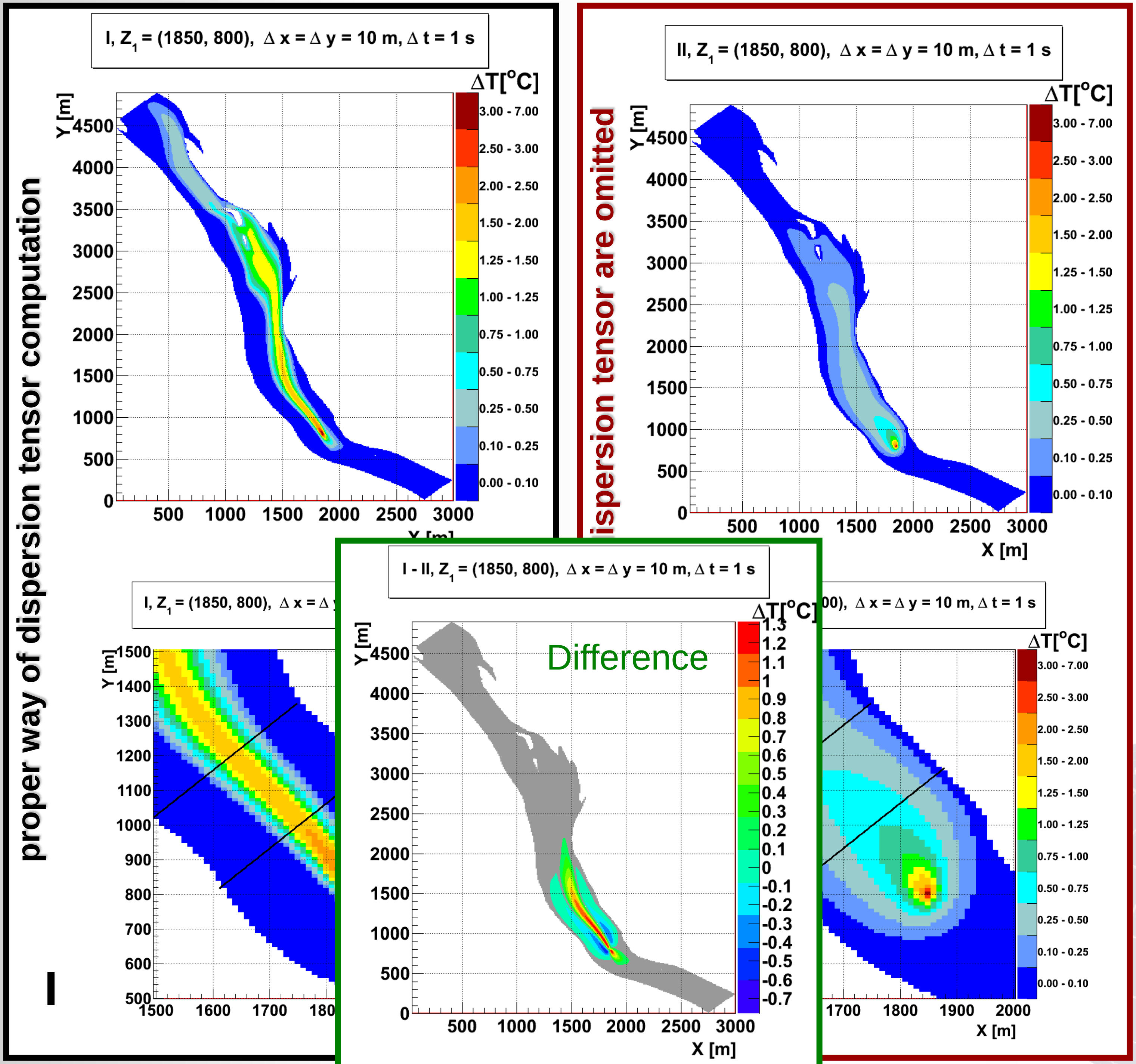
- The best source of information about the dispersion coefficients for an actual river is a tracer experiment

Determination of dispersion coefficients

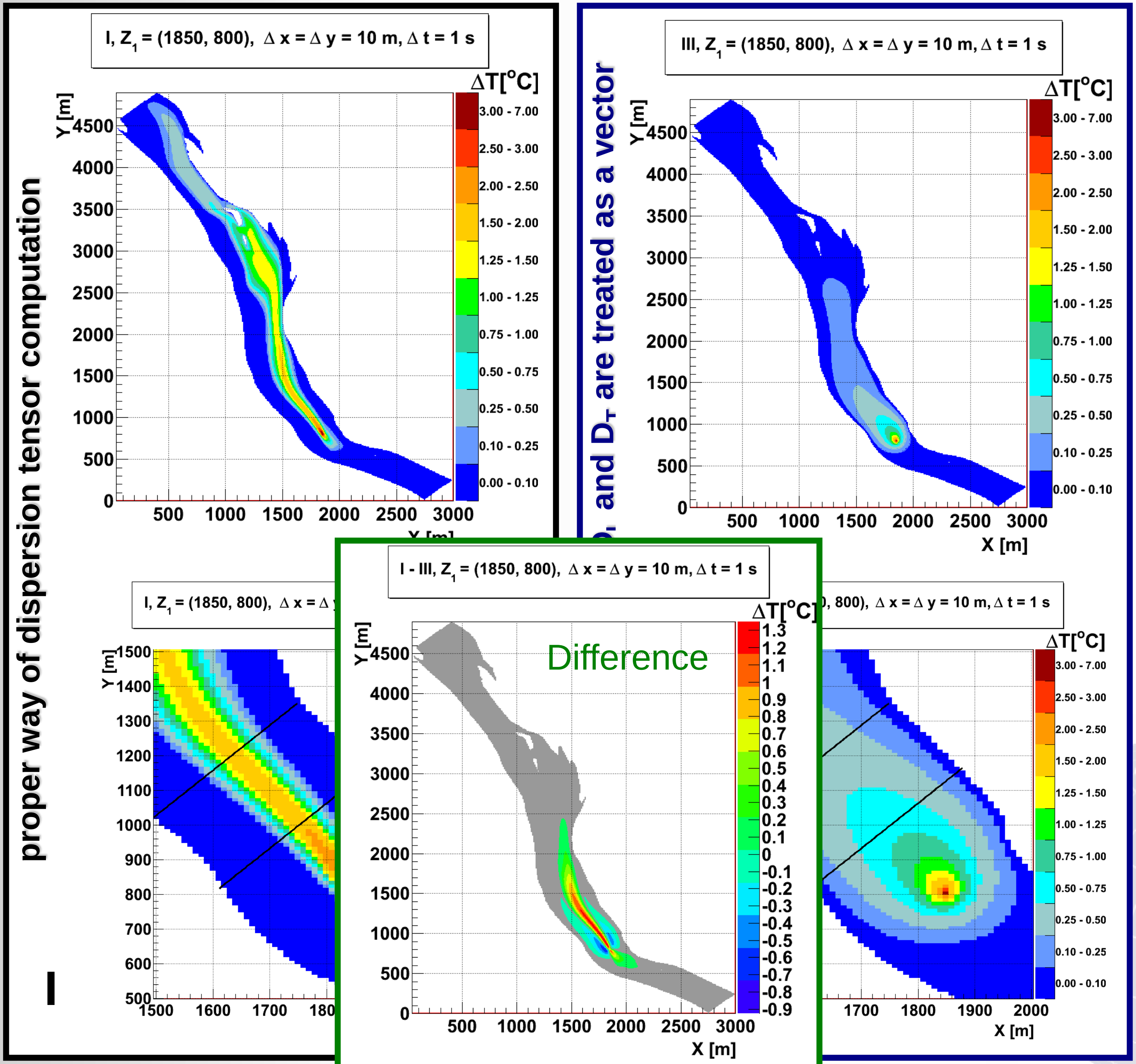
$$\mathbf{D} = \begin{bmatrix} D_{xx} & \cancel{D_{xy}} \\ \cancel{D_{yx}} & D_{yy} \end{bmatrix}$$

✓ **Any kind of simplifications, which lead to omitting the off diagonal components, introduce some (possibly serious) error**

(see details: Rowiński & Kalinowska, River Flow 2006)



Predicted distribution of the temperature increase (Δ*T*) for continuous discharge in the middle of the channel at point *Z1*



Predicted distribution of the temperature increase (Δ*T*) for continuous discharge in the middle of the channel at point *Z1*

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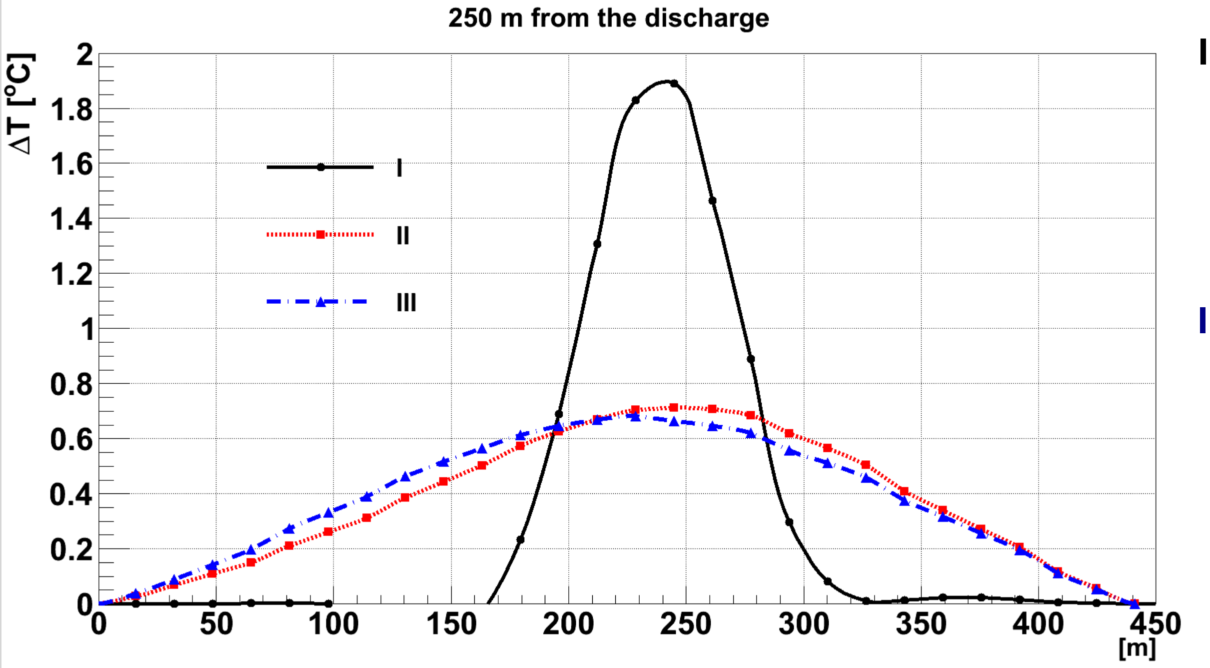
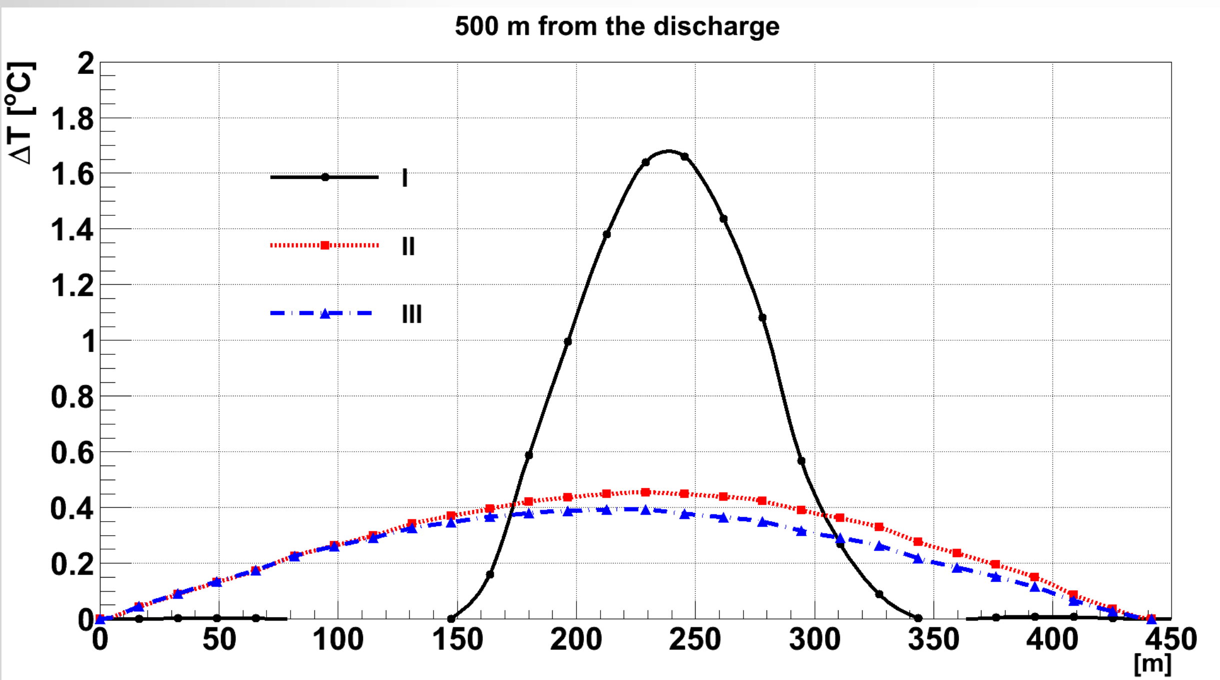




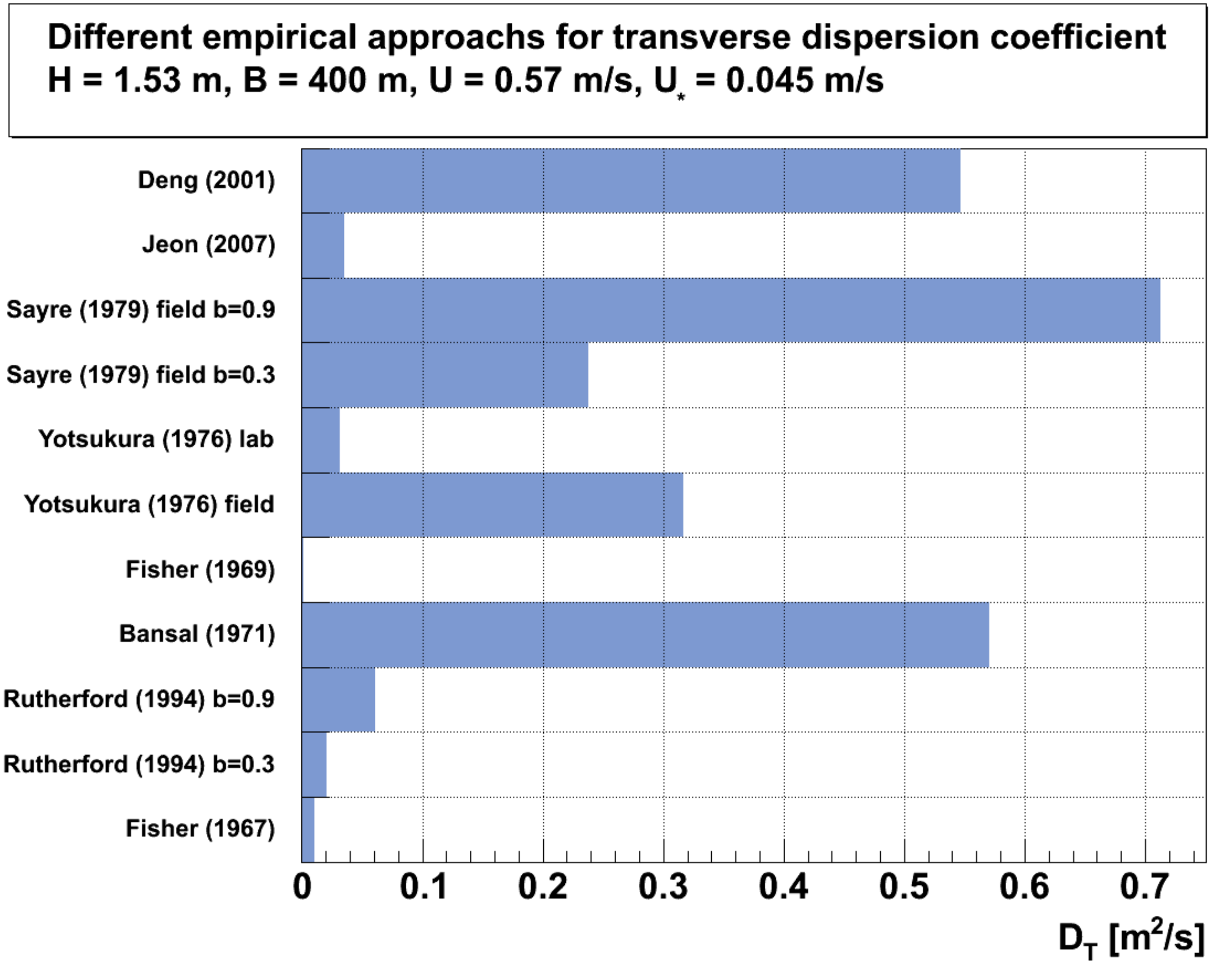
I – with the proper way of dispersion tensor computation,

II – while the off-diagonal elements of dispersion tensor are omitted,

III – while the dispersion coefficients DL and DT are treated as a vector

Temperature increase distribution in case of continuous discharge in the middle of the channel at point Z1 = (1850m, 800m) across the cross-sections located at 250 and 500 m from the discharge point

Determination of dispersion coefficients



H – averaged river depth,
B – averaged river width,
U – averaged velocity,
*U** – averaged shear velocity

Transverse dispersion coefficient D_T for the considered reach of the Vistula River calculated using several formulae (taking into account different hydraulic parameters).

Conclusions

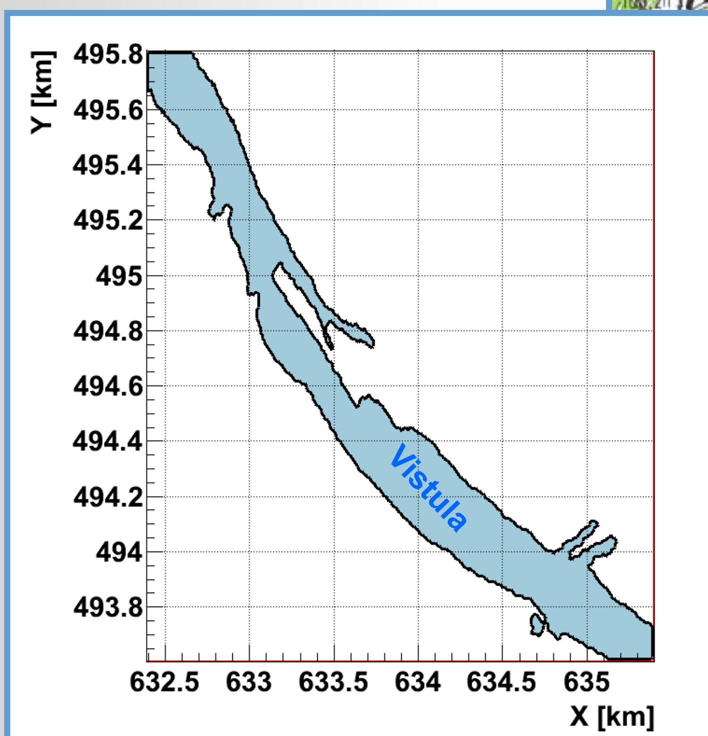
- Solving practical problems concerning the threats caused by heated water discharged into a river usually we deal with the limited data, time and finances, therefore the simplifications of the problem are often inevitable.
- Some of those simplifications are admissible under certain conditions, but some cause unacceptable errors.
- The simplifications of dispersion coefficients may influence the obtained results. The resulting error appears both in temperature distribution shapes and in the values of temperature increase when the dispersion tensor is not compute in the proper way.
- The determination of longitudinal and transverse dispersion coefficients may be difficult in particular case.
- Detailed information can be found in:
  - Kalinowska et al., 2012; Acta Geophysica, 60(1), 214-231

    „Scenarios of the spread of a waste heat discharge in a river – Vistula River case study";
  - Kalinowska & Rowiński, Hydrology and Earth System Sciences, Vol.16, No.11, 4177-4190, 2012

    „Uncertainty in computations of the spread of warm water in river – lessons from environmental impact assessment".

Drugi przykład

Study area



- Given reach of the Vistula River has semi natural braided channel geometry and is protected by *Nature 2000* protocol.

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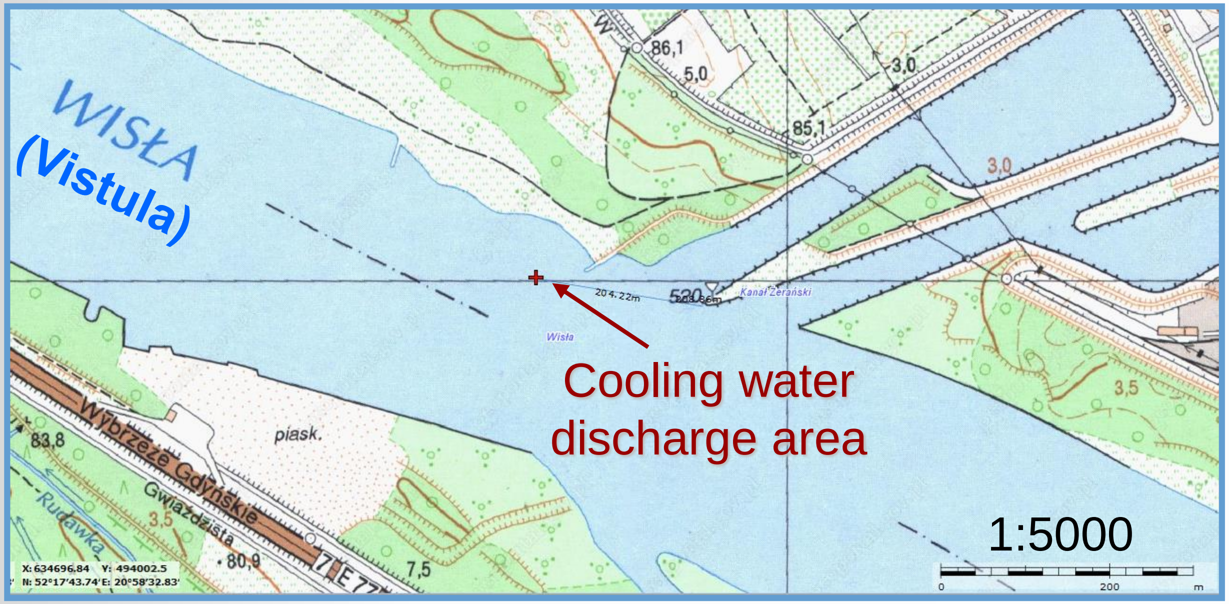
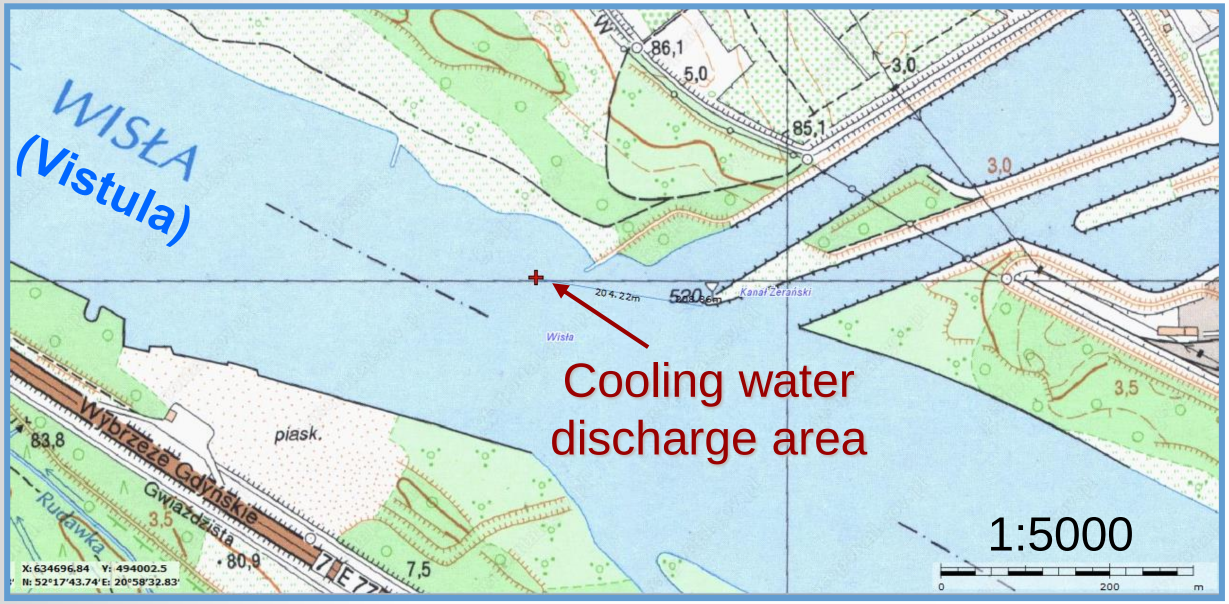
Study area



http://maps.geoportal.gov.pl/

- The cooling water discharges sites are being designed to minimize heat effects on local fish communities and the proposed model is supposed to aid this designing strategy.

Study area



http://maps.geoportal.gov.pl/

- **Discharge** of warm water with constant intensity of 9 m^3/s;
- **Temperature** of discharged water:
  - 8°C higher than the temperature of ambient river water;
  - does not exceed 35°C.

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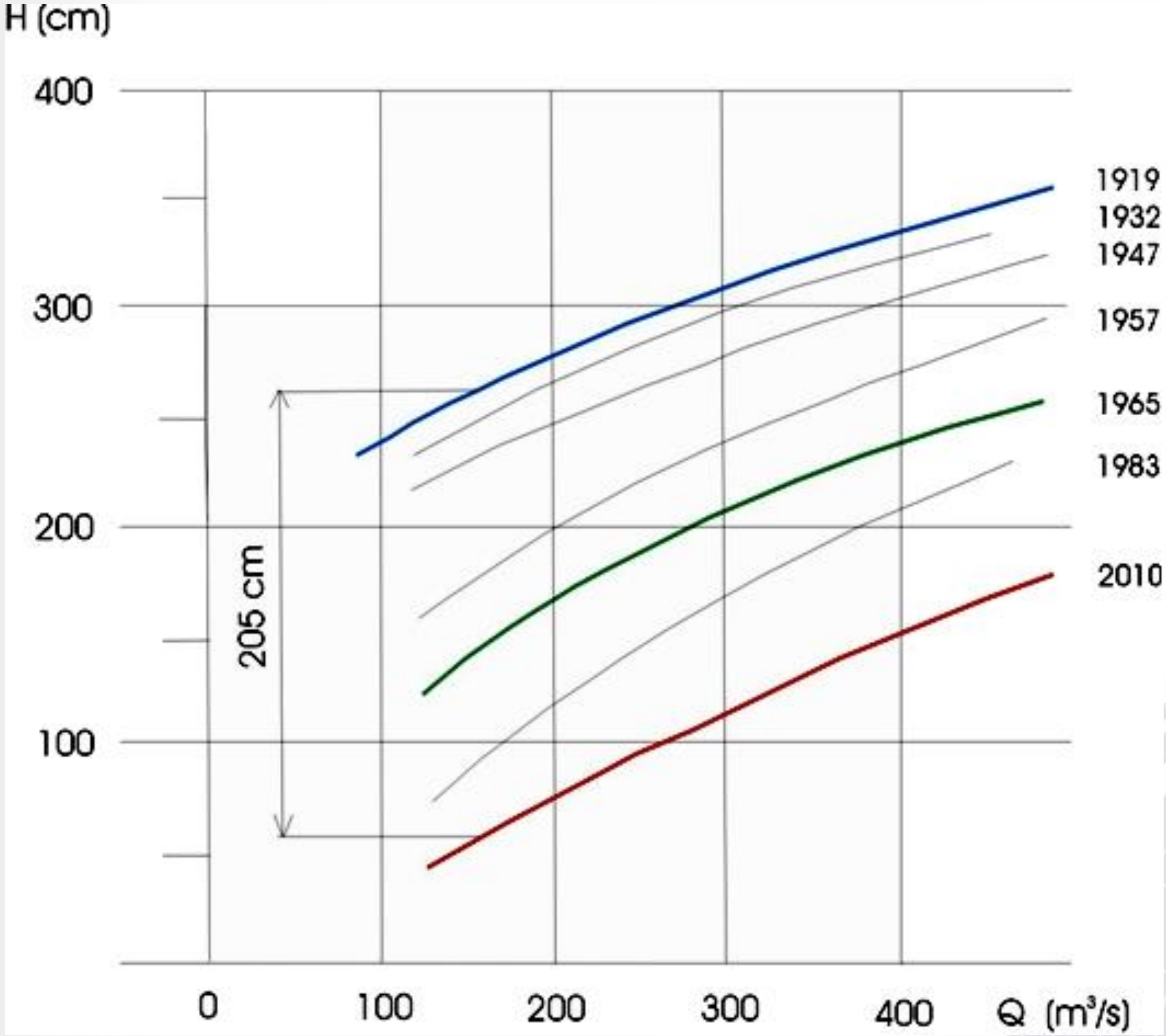
Rating curves for low flows at *Port Praski* (km 513,3, Pz = 76,067 m n.p.m. Kr)



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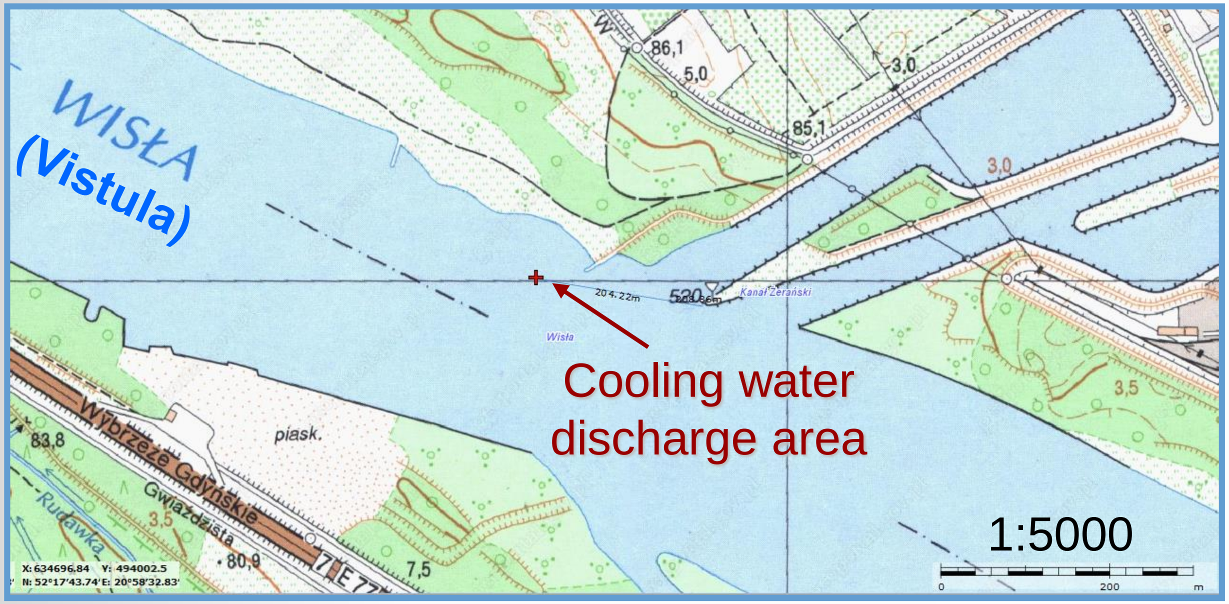
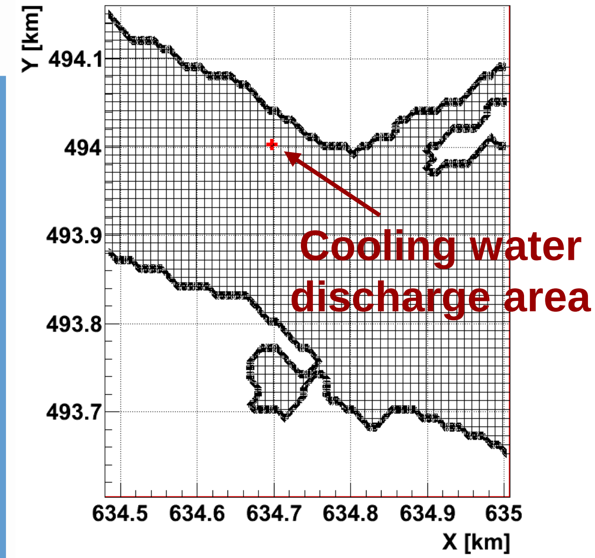
Study area



http://maps.geoportal.gov.pl/

Computational mesh, Q = 200 m^3/s



- ❑ The computations have been performed for the mean low-flows of the river Q = 200 m^3/s

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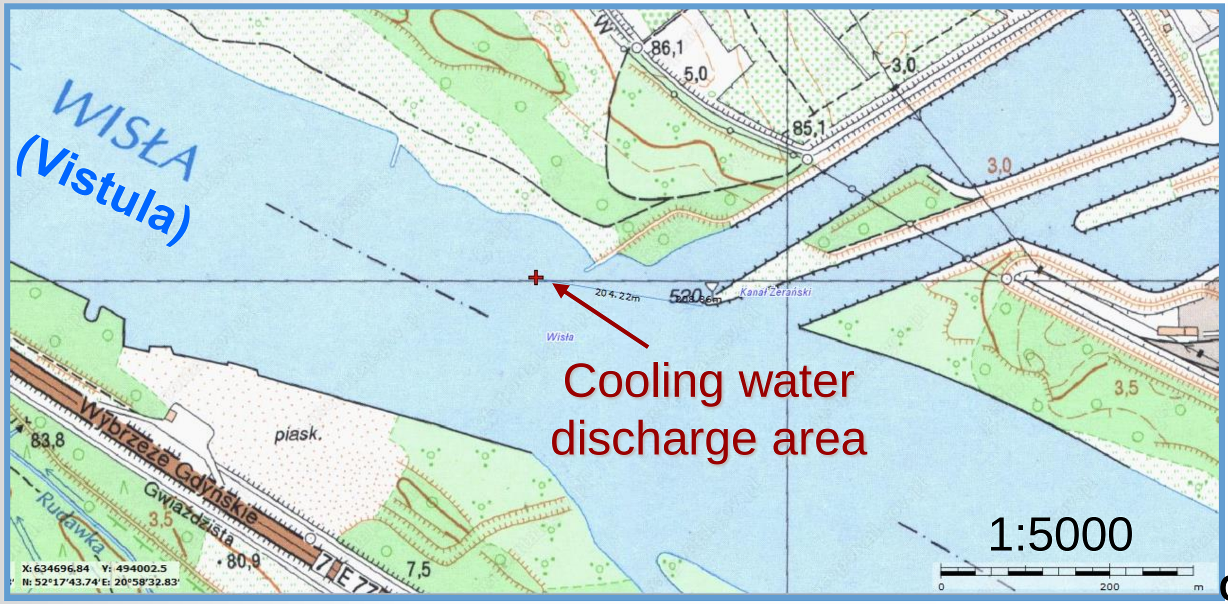
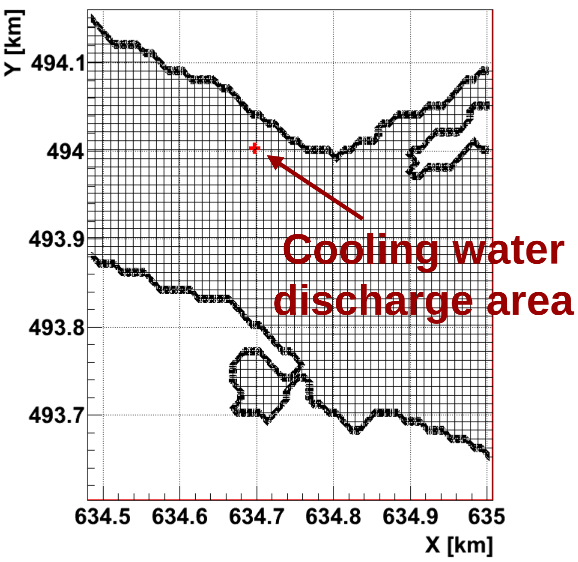
Computations

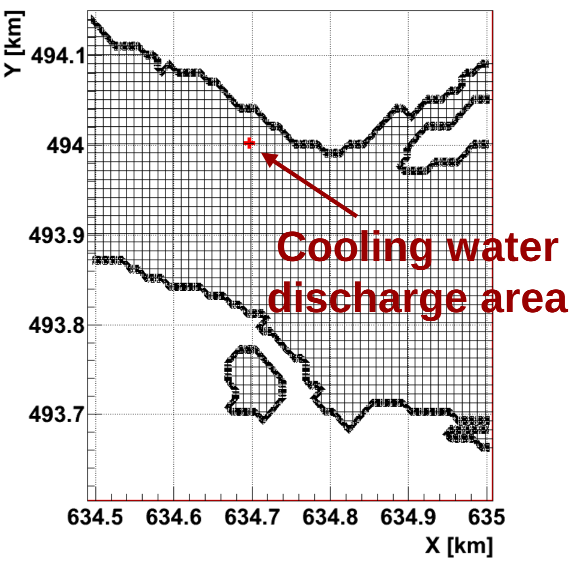


http://maps.geoportal.gov.pl/

Computational mesh, Q = 200 m³/s

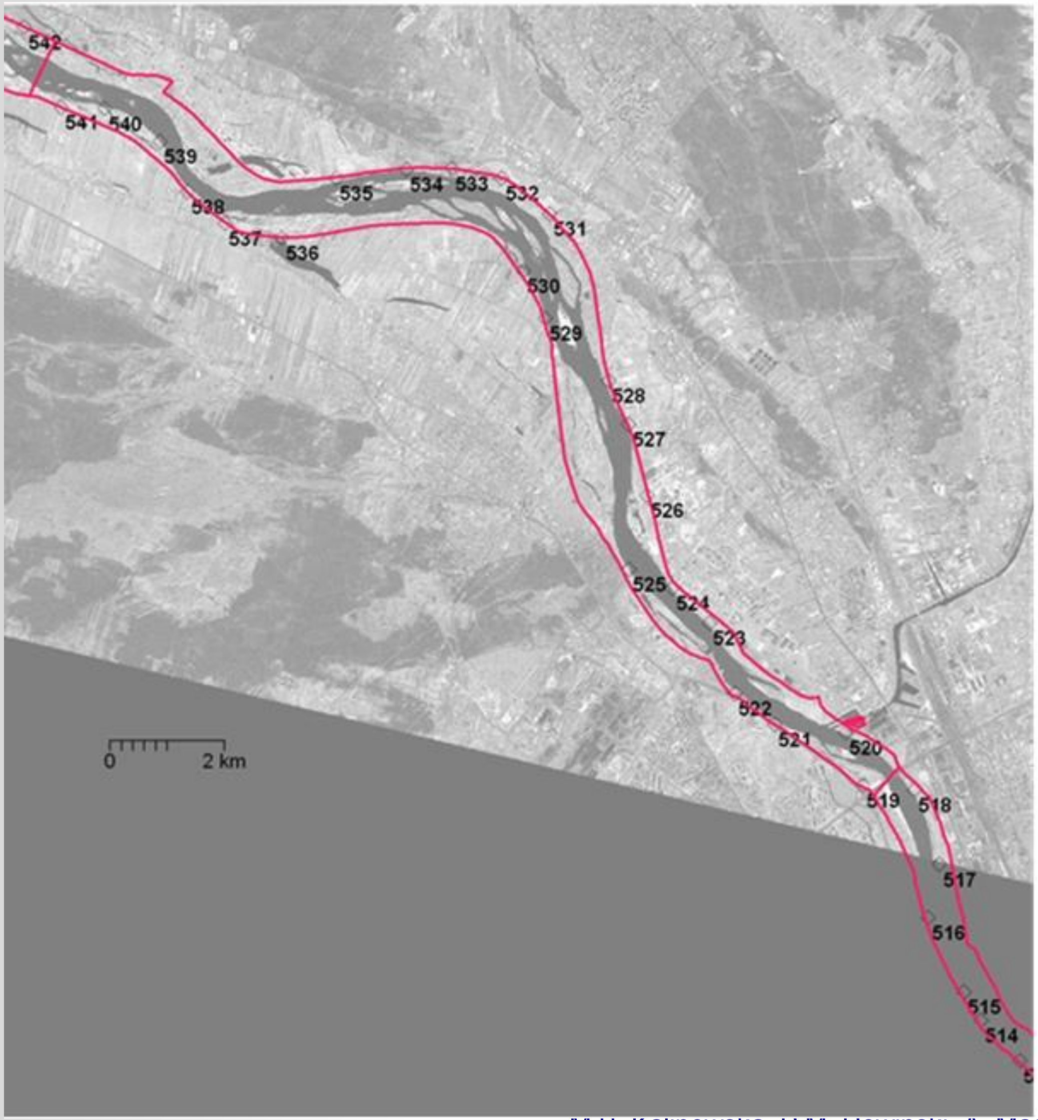


Computational mesh, Q = 100 m³/s



- The computations have been done for the mean low-flows of the river Q = 200 m^3/s
- Additionally the calculations have been performed for the lowest possible value of the flow Q = 100 m^3/s

Vistula reach where computations based on CCHE2D were performed

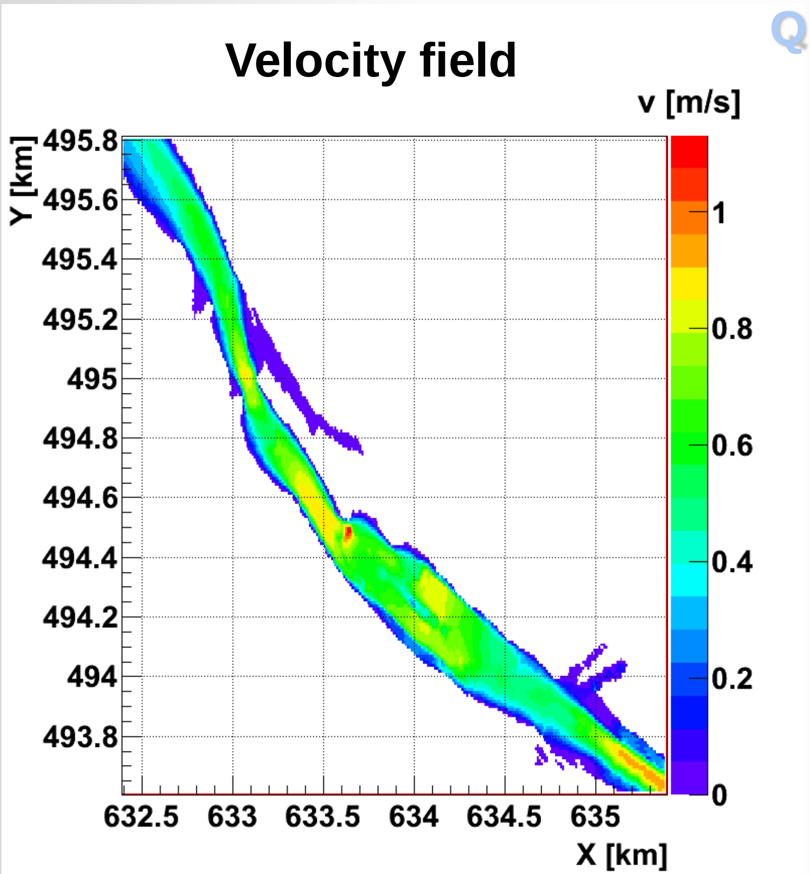


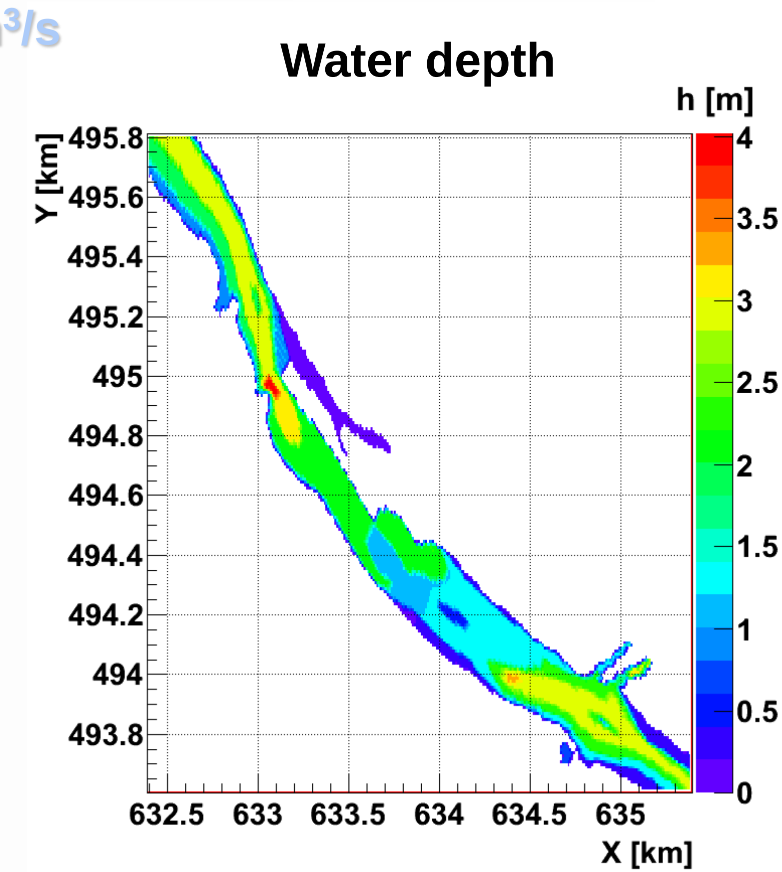
Landsat 7 picture

Courtesy of Global Land Cover Facility, Institute for Advanced Computer Studies, University of Maryland, College Park, USA

Computational Results

$Q = 200\ m^3/s$





used as the input to the heat transport (RivMix) model

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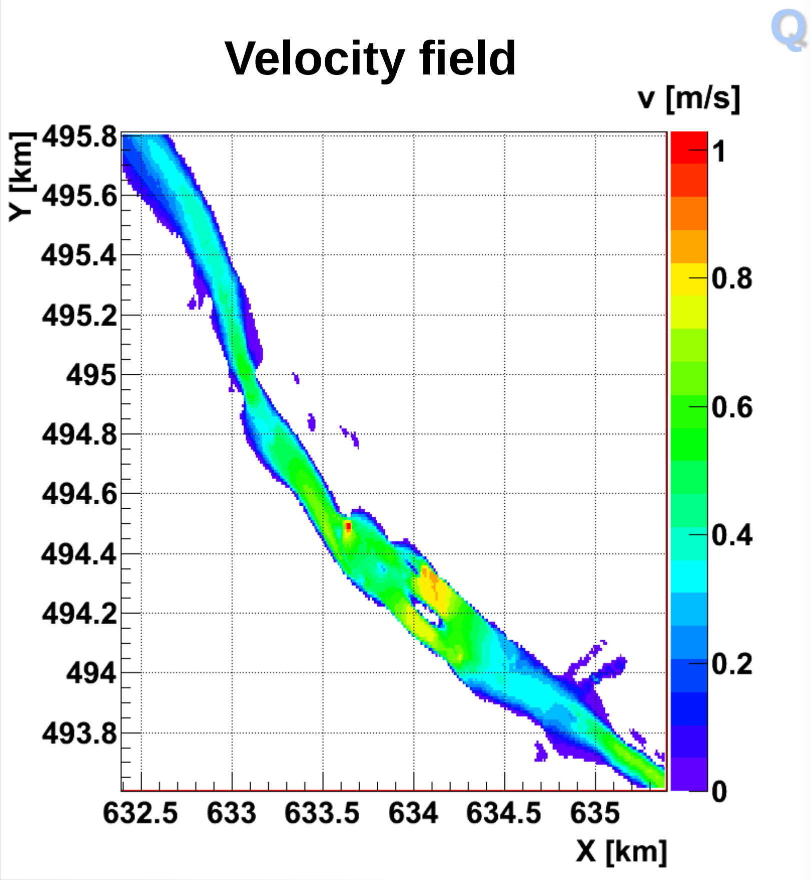
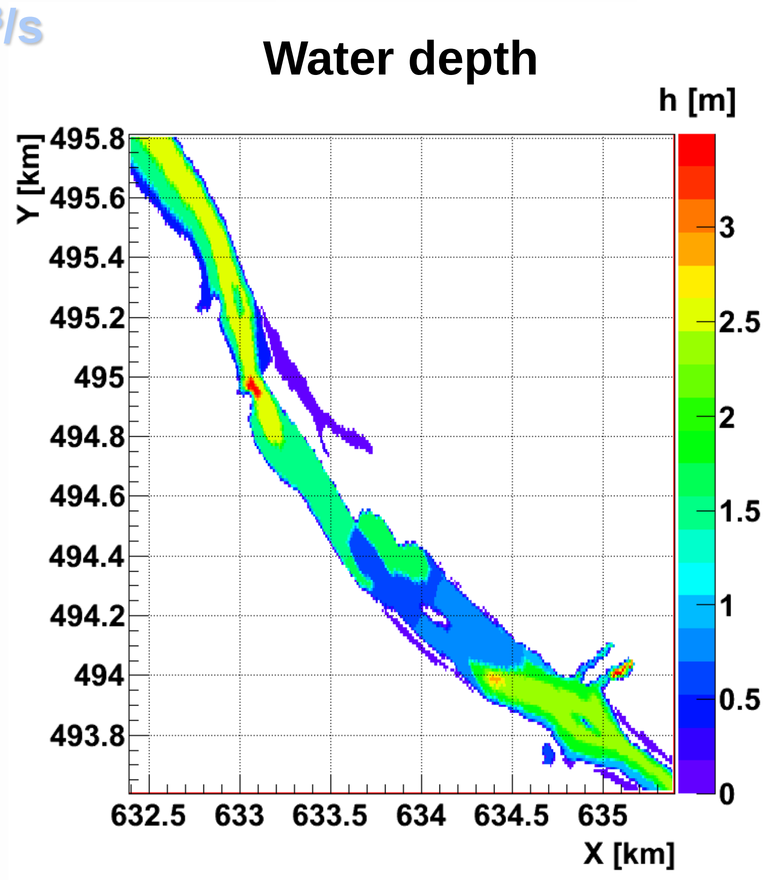
Computations

Q = 100 m^3/s



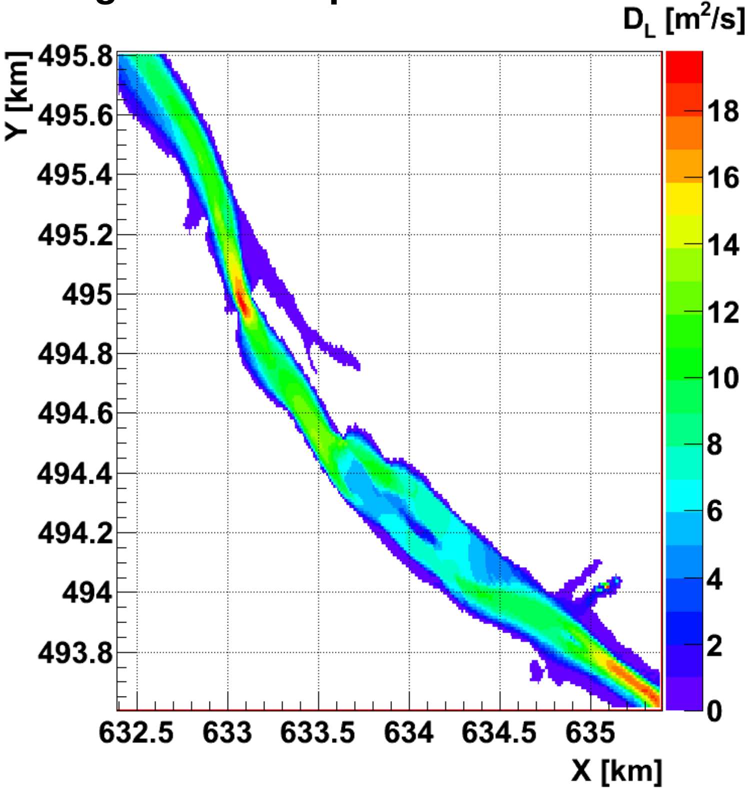


used as the input to the heat transport (RivMix) model

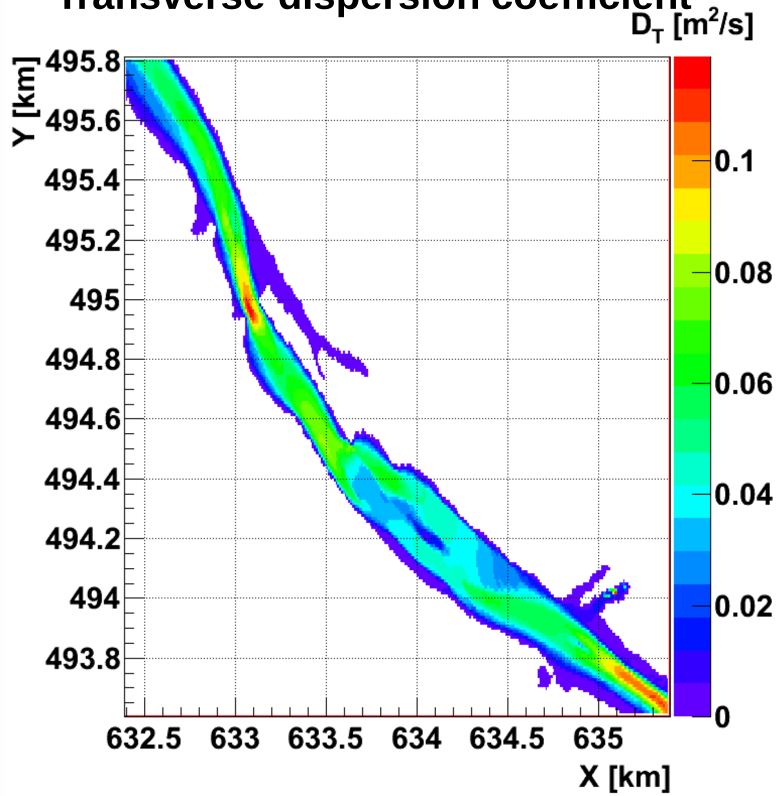
Computations

Q = 200 m³/s

Longitudinal dispersion coefficient



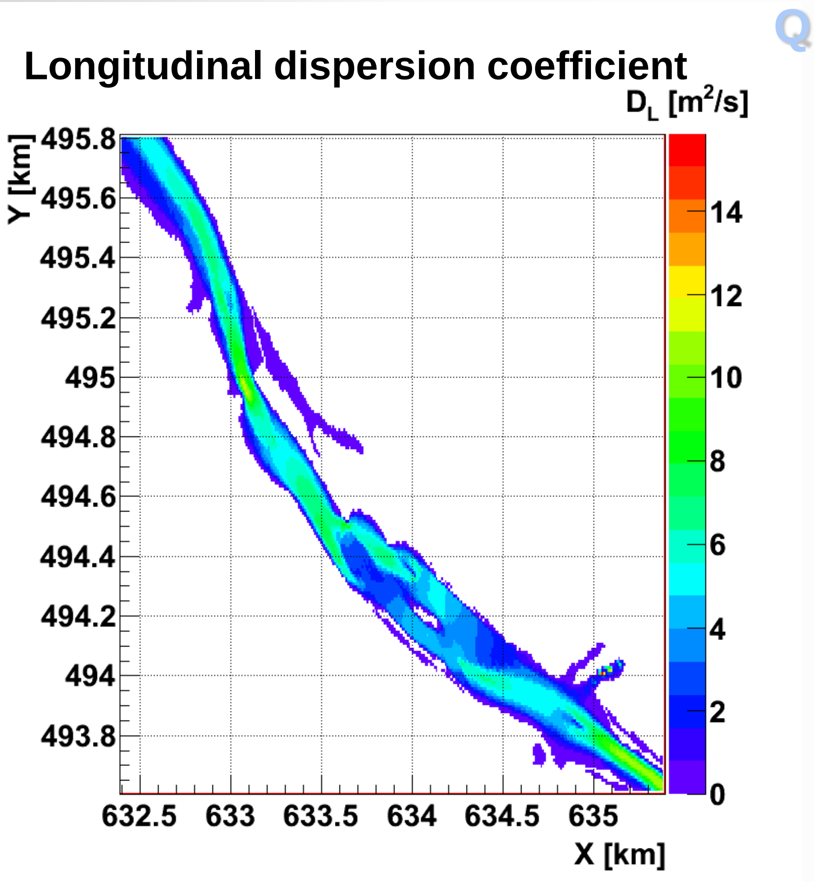
Transverse dispersion coefficient

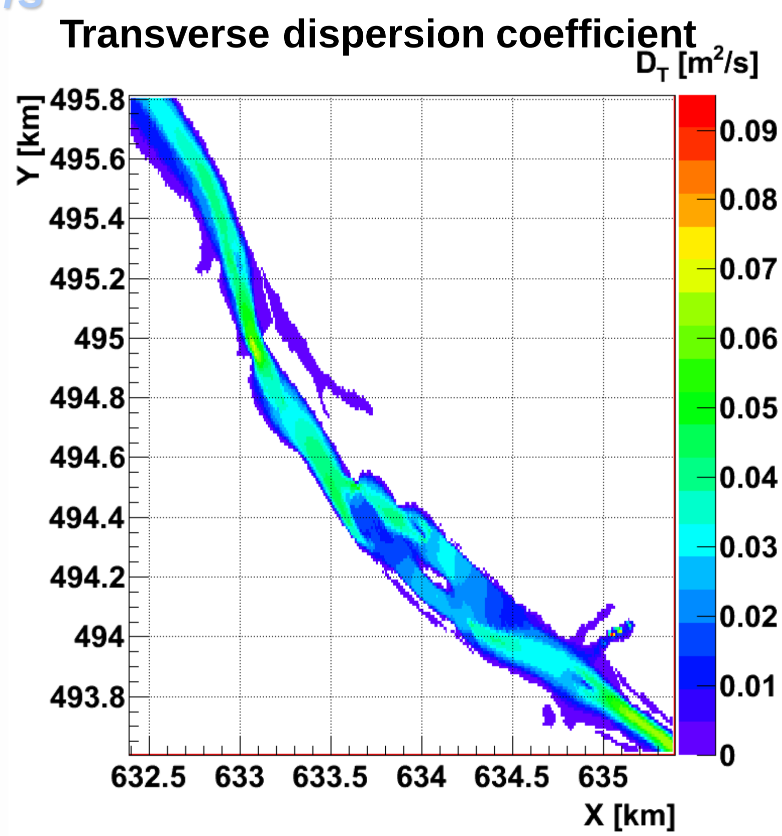


used as the input to the heat transport (RivMix) model

Computations

Q = 100 m^3/s

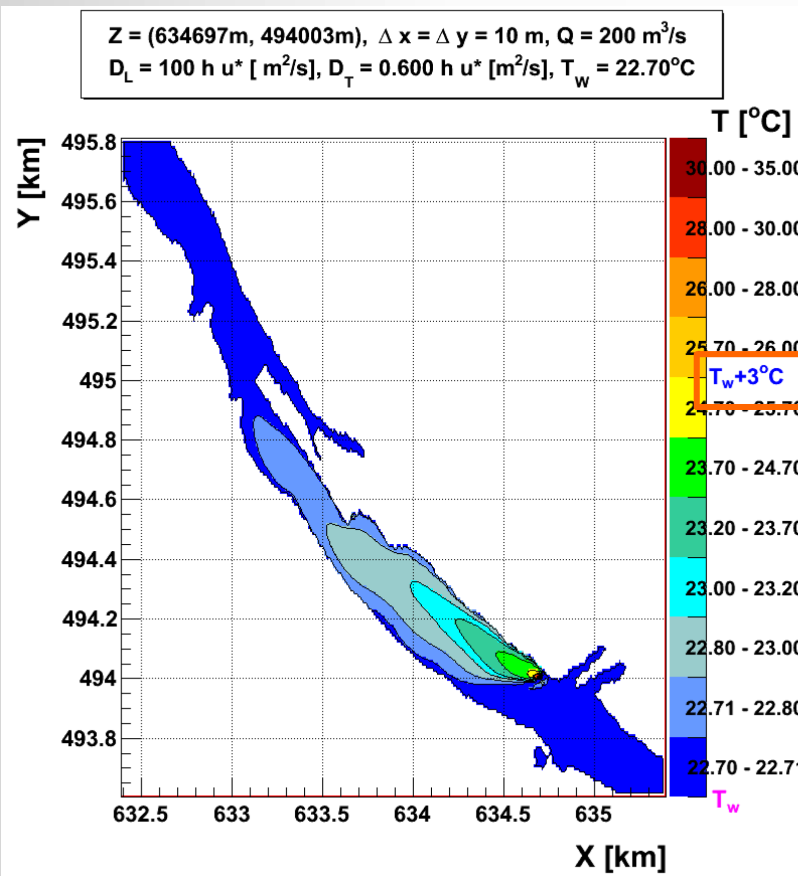


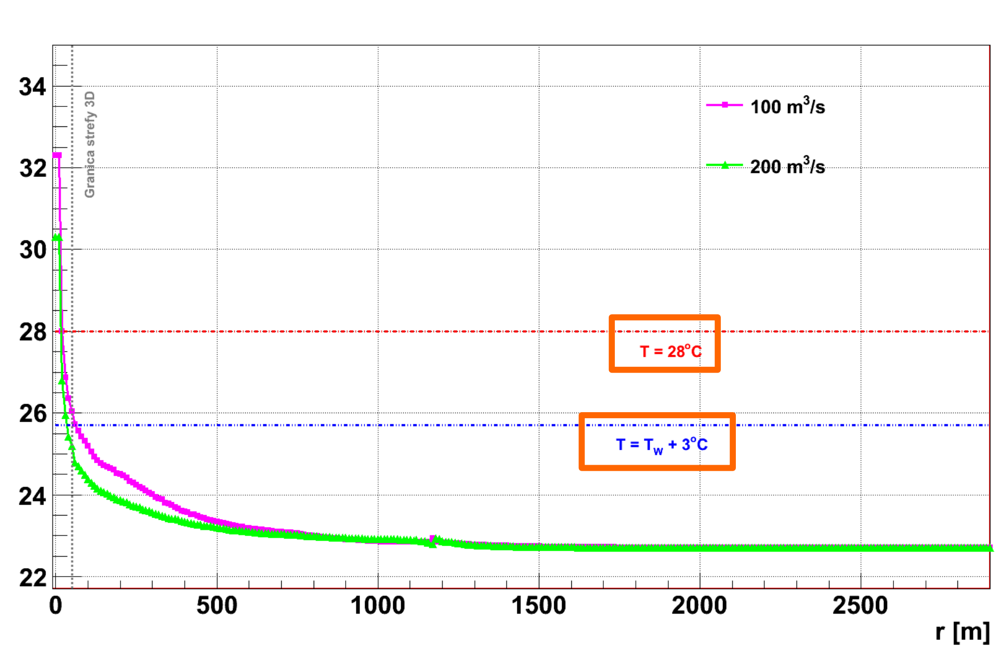


used as the input to the heat transport (RivMix) model

Results – summer time

- Averaged summer temperature in Vistula River: 22.7°C
- Temperature of discharged water: 30.7°C (ΔT = 8°C)





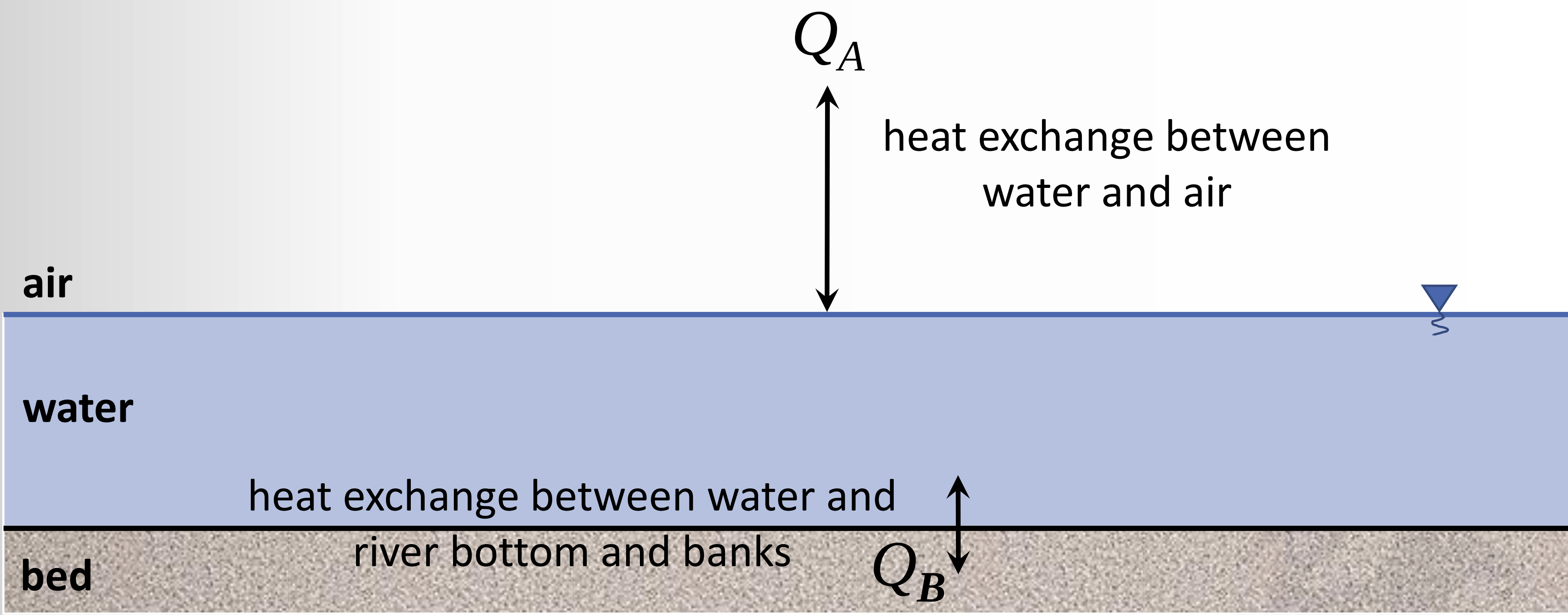
Uncertainty in computations

- Problems encountered during solving the practical cases:
  - limited data and information
  - measurement errors
  - simplification of transport equation
  - errors introduced by the models used in the calculation, numerical errors
  - geometry
    - insufficient number of the measured cross-sections
    - interpolation procedures
  - setting the Initial and boundary conditions
  - determination of coefficients
    - dispersion coefficients

(see details: Kalinowska & Rowiński, HESSD 2012)

Heat exchange between a river and its environment

- In particular, the following processes may be significant:



tributaries

rainfall

groundwater flows

biological processes

chemical processes

sediment

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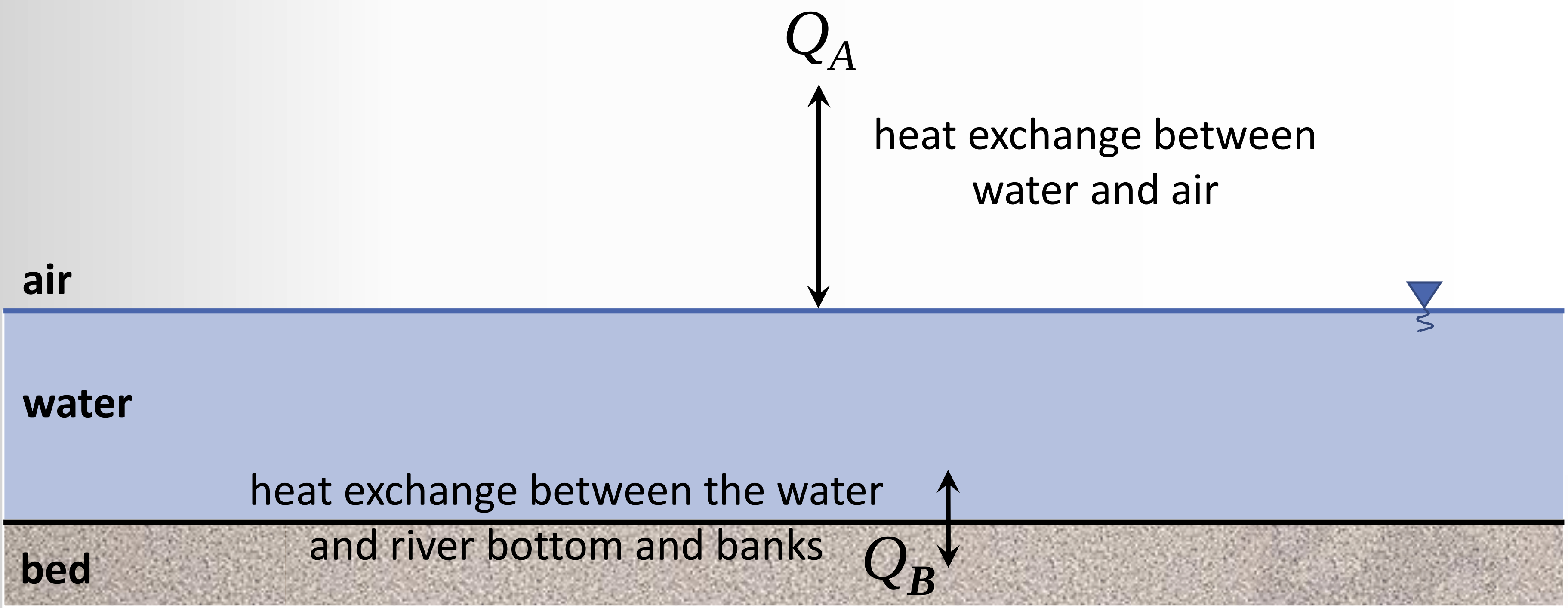
Heat exchange between a river and its environment

- In particular, the following processes may be significant:



Finally the source function *Q* will be a sum of all functions describing heating or cooling processes taken into account:

$$Q = Q_A + Q_B + \cdots$$

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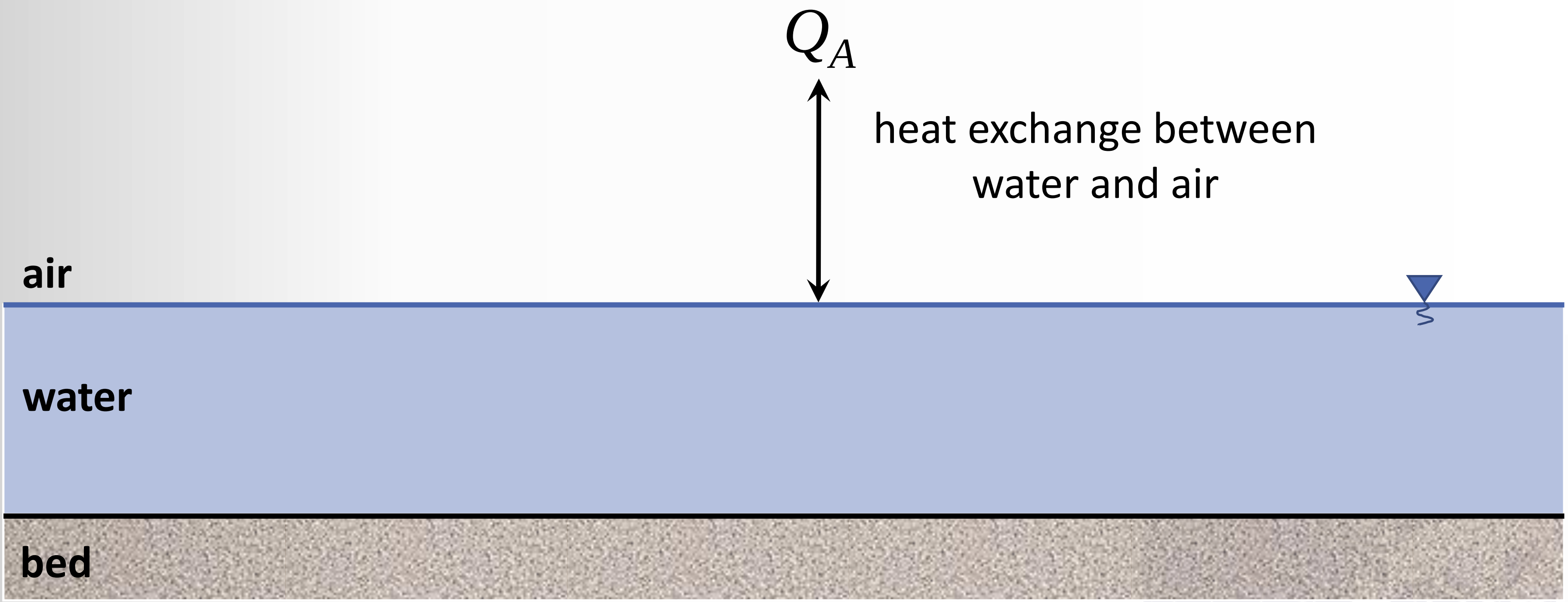
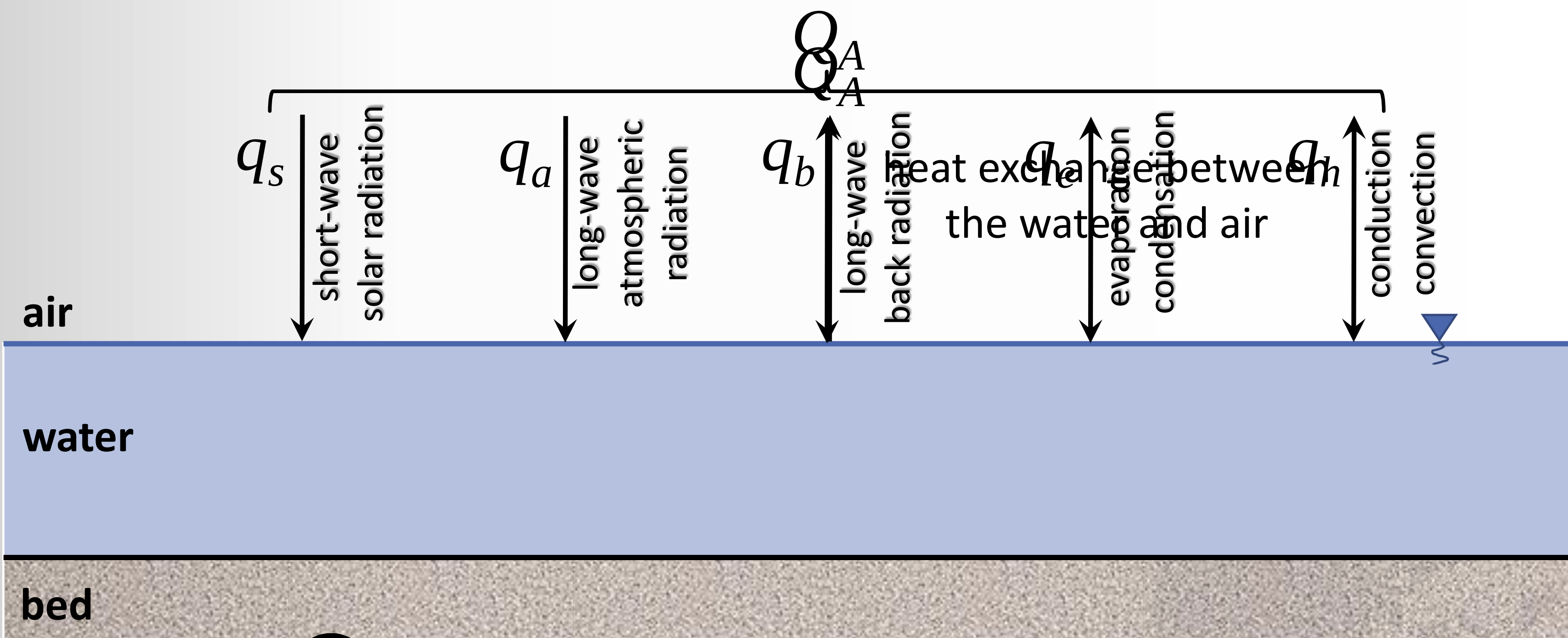
Heat exchange with the atmosphere

- A huge amount of heat exchange between water and its environment occurs through the water/air interface



Heat exchange with the atmosphere

- The heat flux results from the energy balance at the water-air interface



$$Q_A = q_s + q_a - q_b \pm q_e \pm q_h$$

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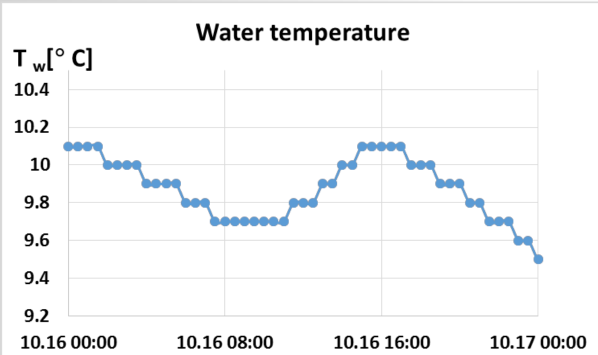
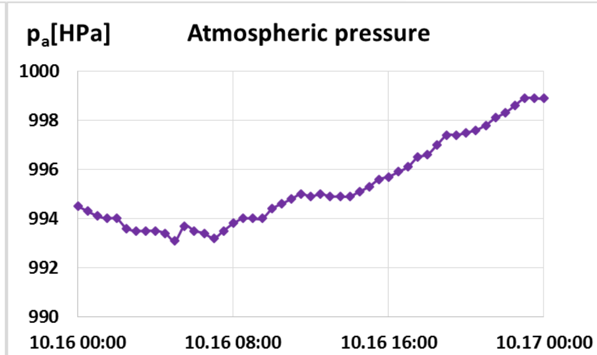
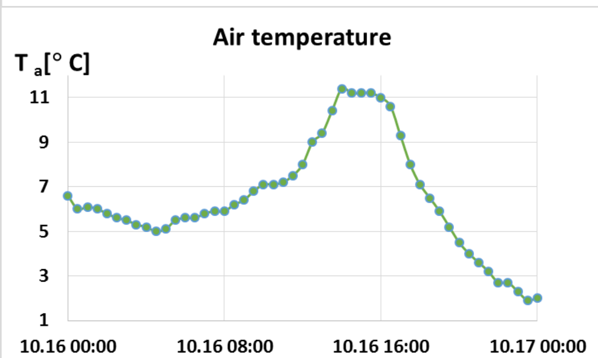
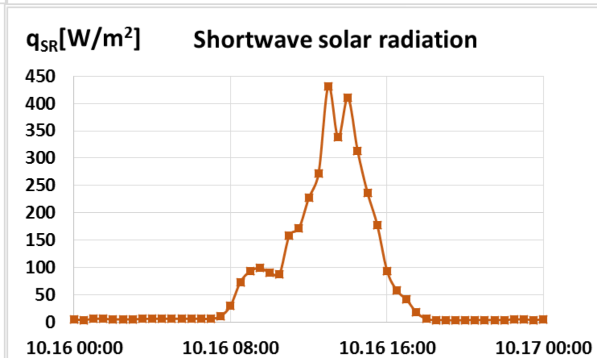
Heat exchange with the atmosphere

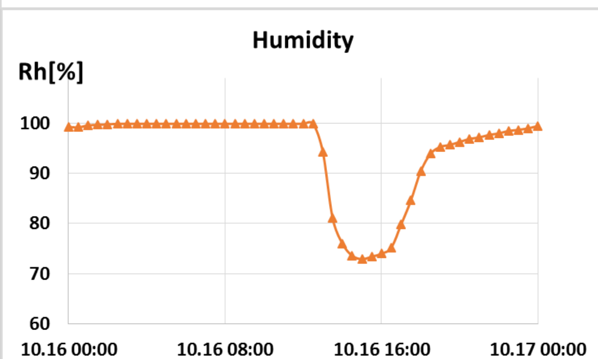
$$Q_A = q_s + q_a - q_b \pm q_e \pm q_h = f(T_w, T_a, Rh, p_a, q_{SR}, u)$$

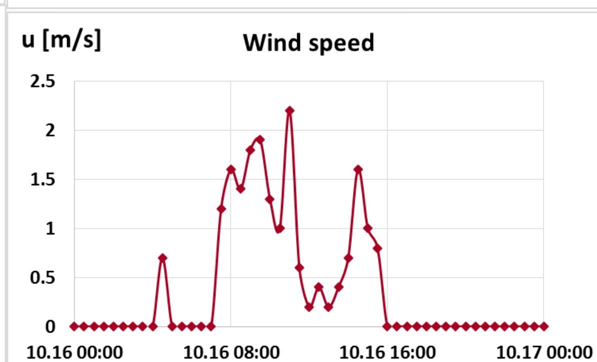












Sample data measured for the River Narew in Poland

Source of data:
Institute of Geopchysics PAS,
and http://npn.meteo.com.pl/

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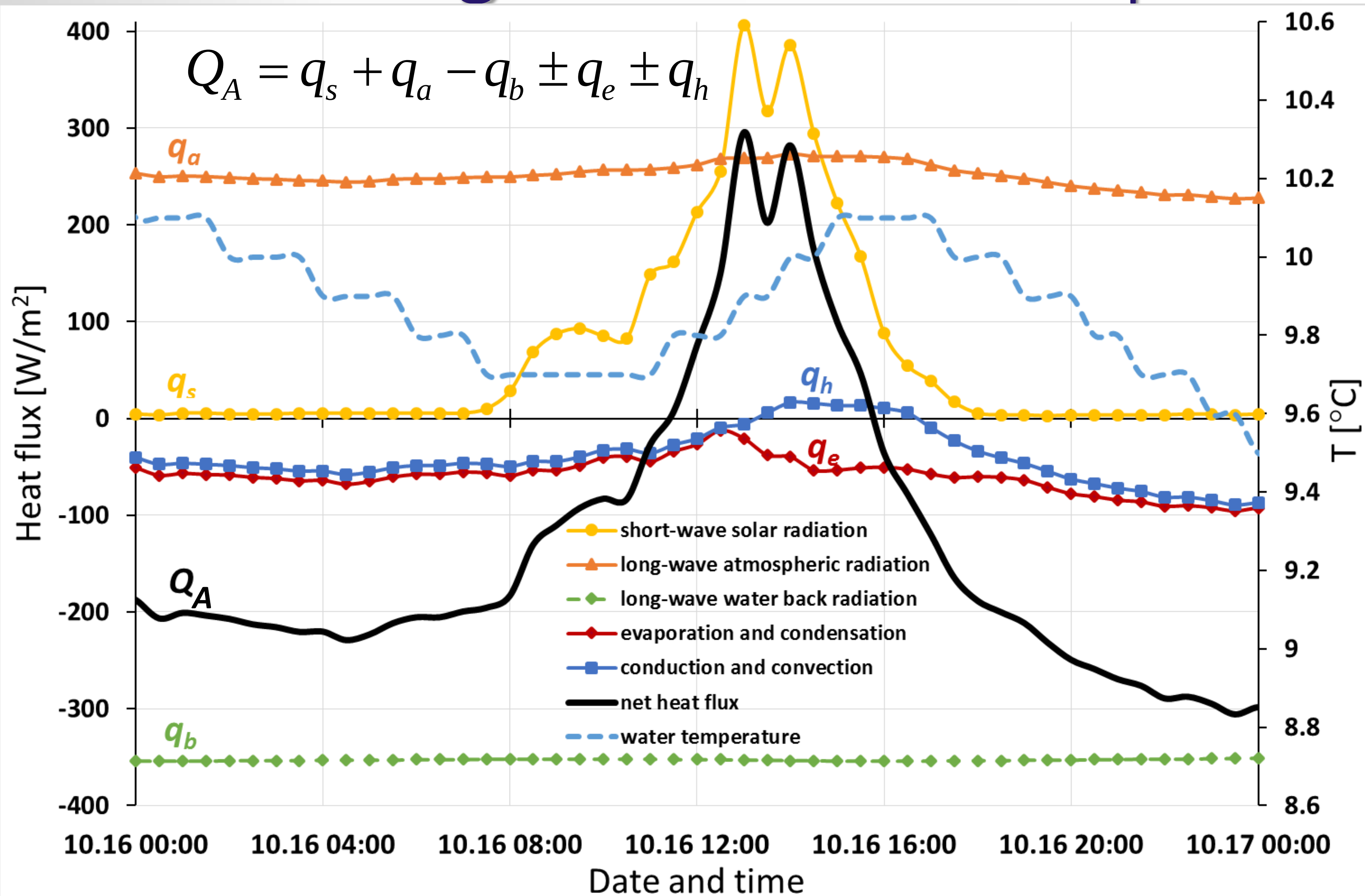
Heat exchange with the atmosphere

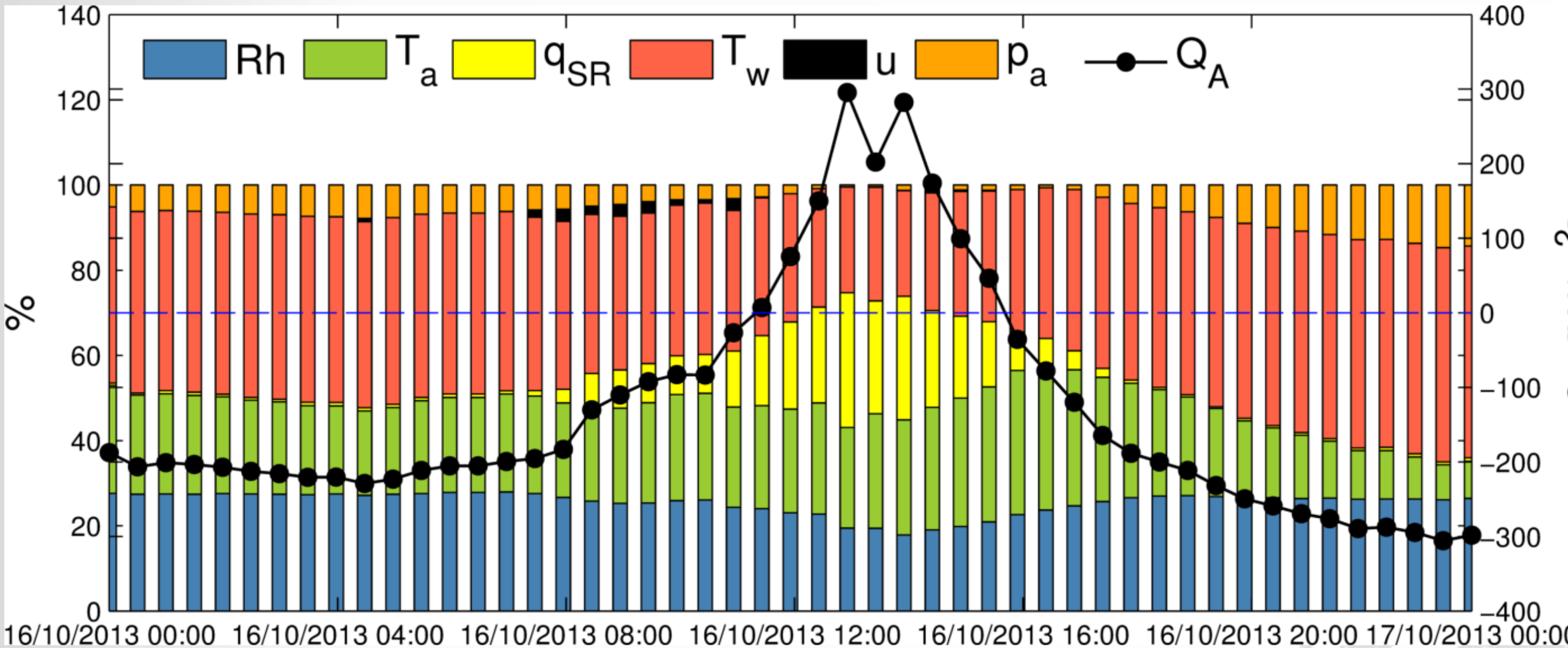


Heat flux terms calculated for the Narew River case study on 16th of October 2013 The meteorological data used for calculation have been obtained from the nearest meteorological station: Narew National Park Weather Station

Importance of input data

$$Q_A = f(T_w, T_a, Rh, p_a, q_{SR}, u)$$

- Percentage of relative sensitivity coefficient



The effect of a small perturbation of input variables on output variable Q_A is assessed by a non-dimensional relative sensitivity coefficient

Rh – humidity
T_a – air temperature
q_{SR} – shortwave solar radiation
T_w – water temperature

u – wind speed
p_a – atmospheric pressure
Q_A – net heat flux

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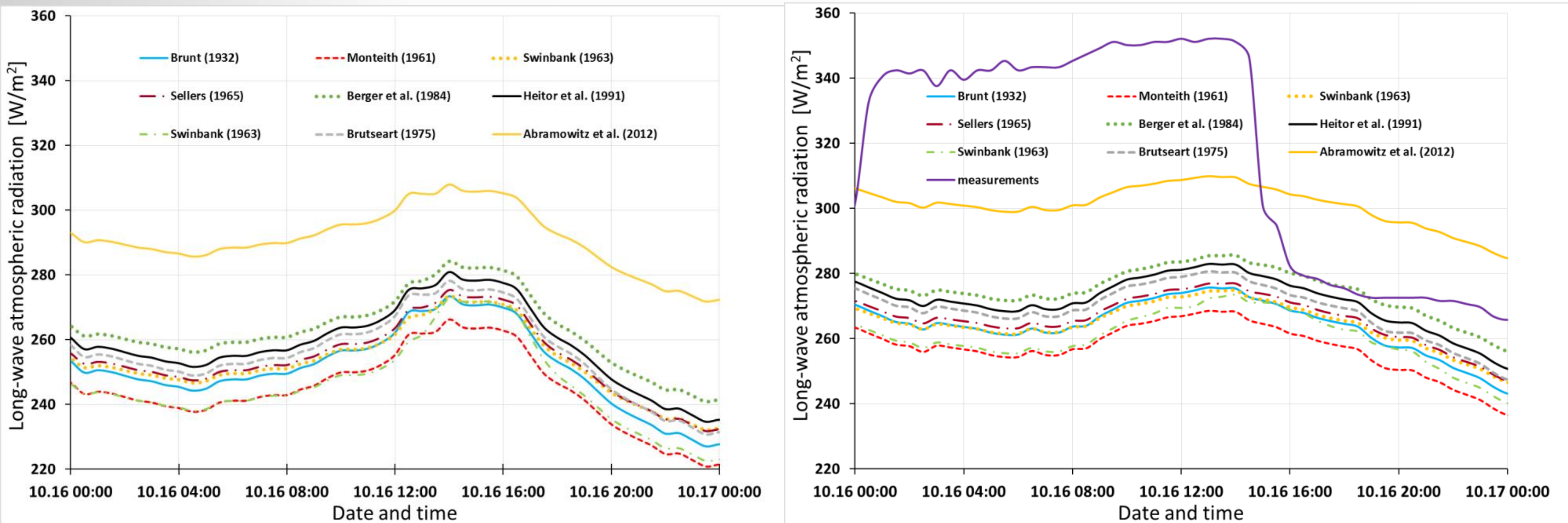
Long wave atmospheric radiation

The long-wave atmospheric radiation depends on the atmospheric emissivity, for which many formulae have been obtained.



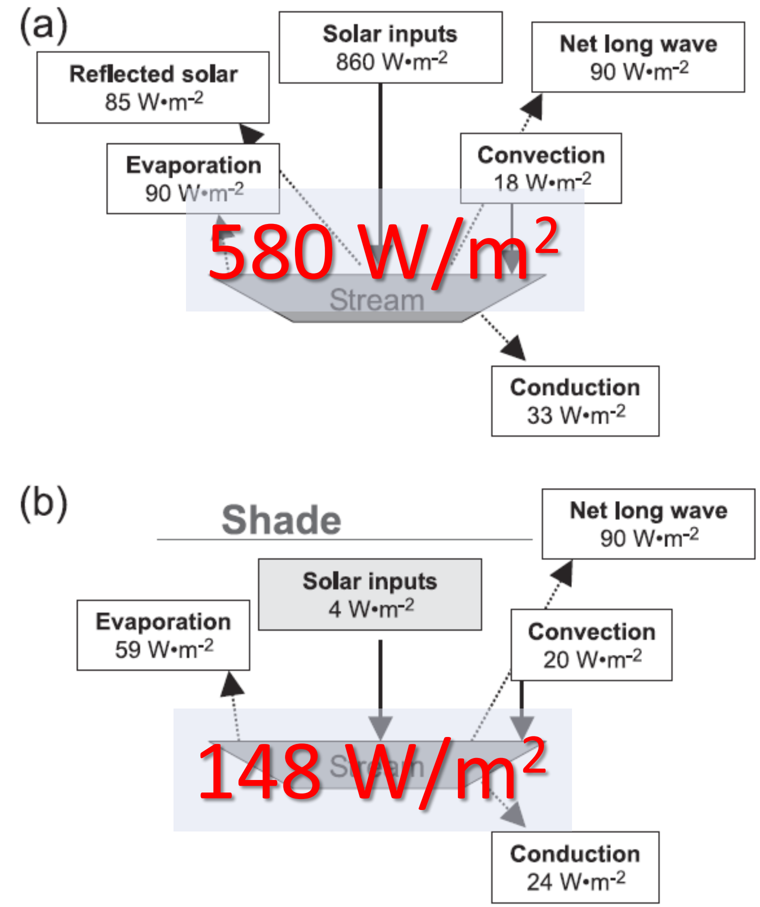
Long-wave atmospheric radiation heat flux for case study on the Narew River on 16th of October 2013 with different formulae for atmospheric emissivity. The meteorological data used for calculation have been obtained from a) Narew National Park Weather Station; b) IGF UW Meteorological observatory (http://metobs.igf.fuw.edu.pl/); 2 and 160 km from the case study area respectively.

Data problem

- Data are usually obtained from local meteorological stations
- But conditions on the river banks may differ significantly from those at the location of these meteorological stations
- The river may be in a valley or may be sheltered from the wind and sun by a large number of trees
- The conditions may also significantly vary along the river channel

Johnson (2004), Can. J. Fish. Aquat. Sci. Vol. 61

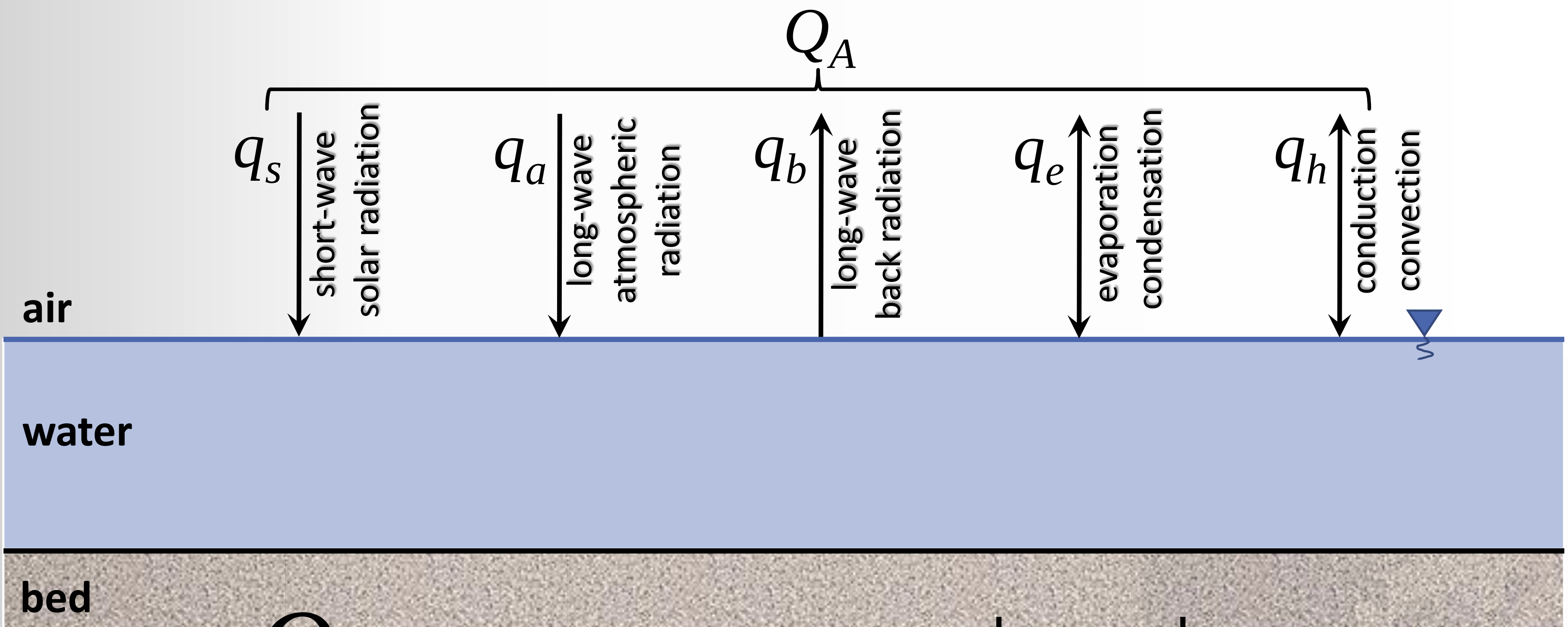
Fig. 7. Heat energy budgets for 1200, 20 July 1997, in the bedrock reach: (*a*) full sun, the sum of fluxes is 580 W·m^{-2} towards the stream; (*b*) under shade, the sum of fluxes is 149 W·m^{-2} away from the stream.



Inaccurate calculations of heat fluxes here may introduce larger error in the final results than their omission.

But when we are calculating the ΔT

- We can neglect the terms not dependent on water temperature



$$Q_A = q_s + q_a - q_b \pm q_e \pm q_h$$

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But when we are calculating the ΔT

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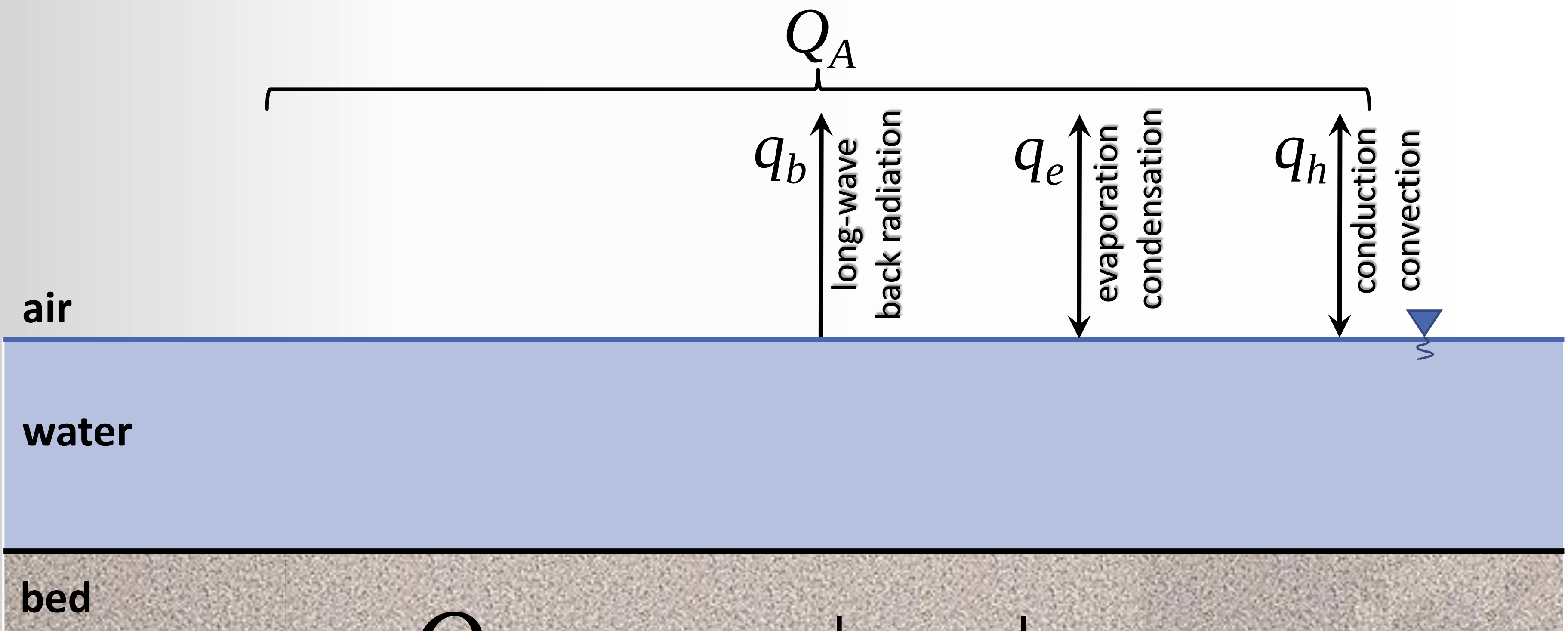

$$Q_A = -q_b \pm q_e \pm q_h$$

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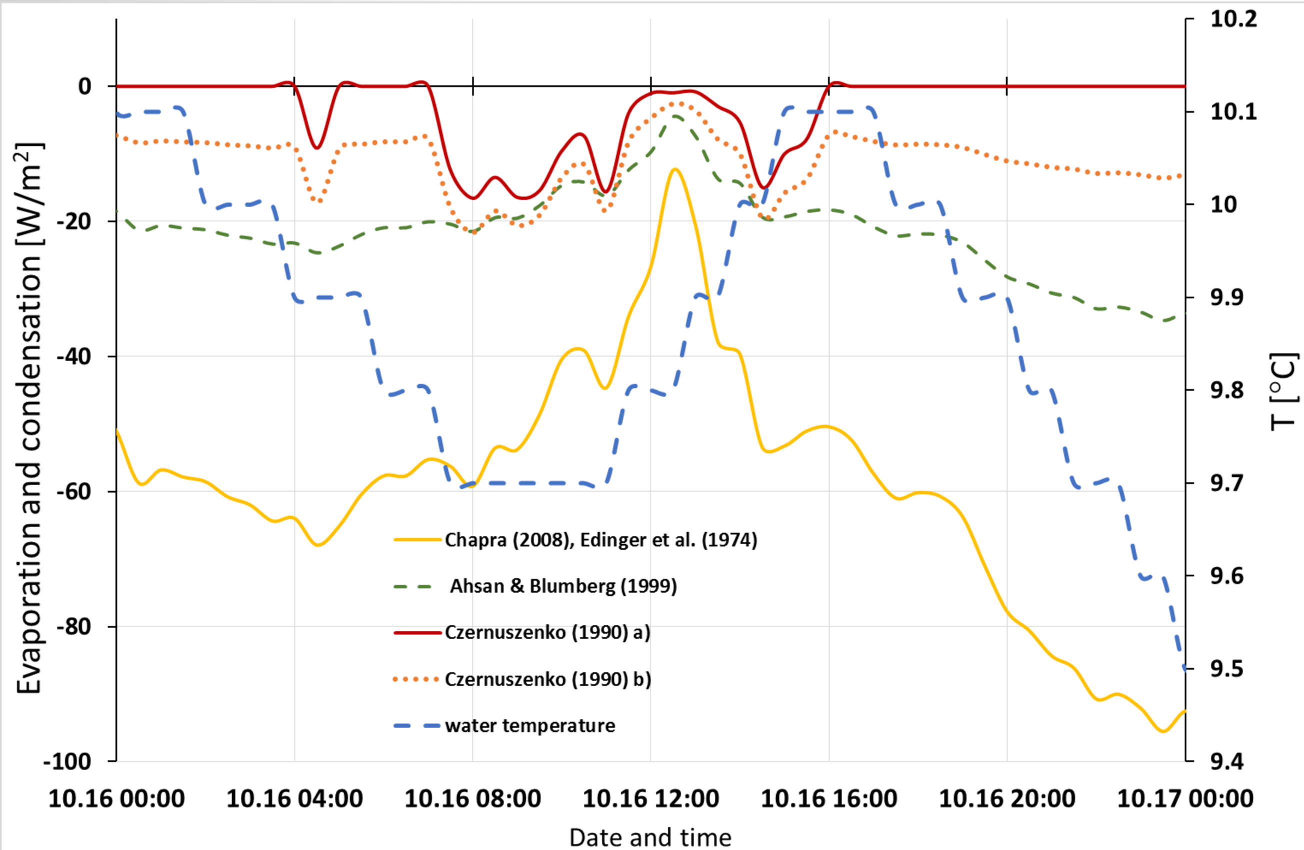
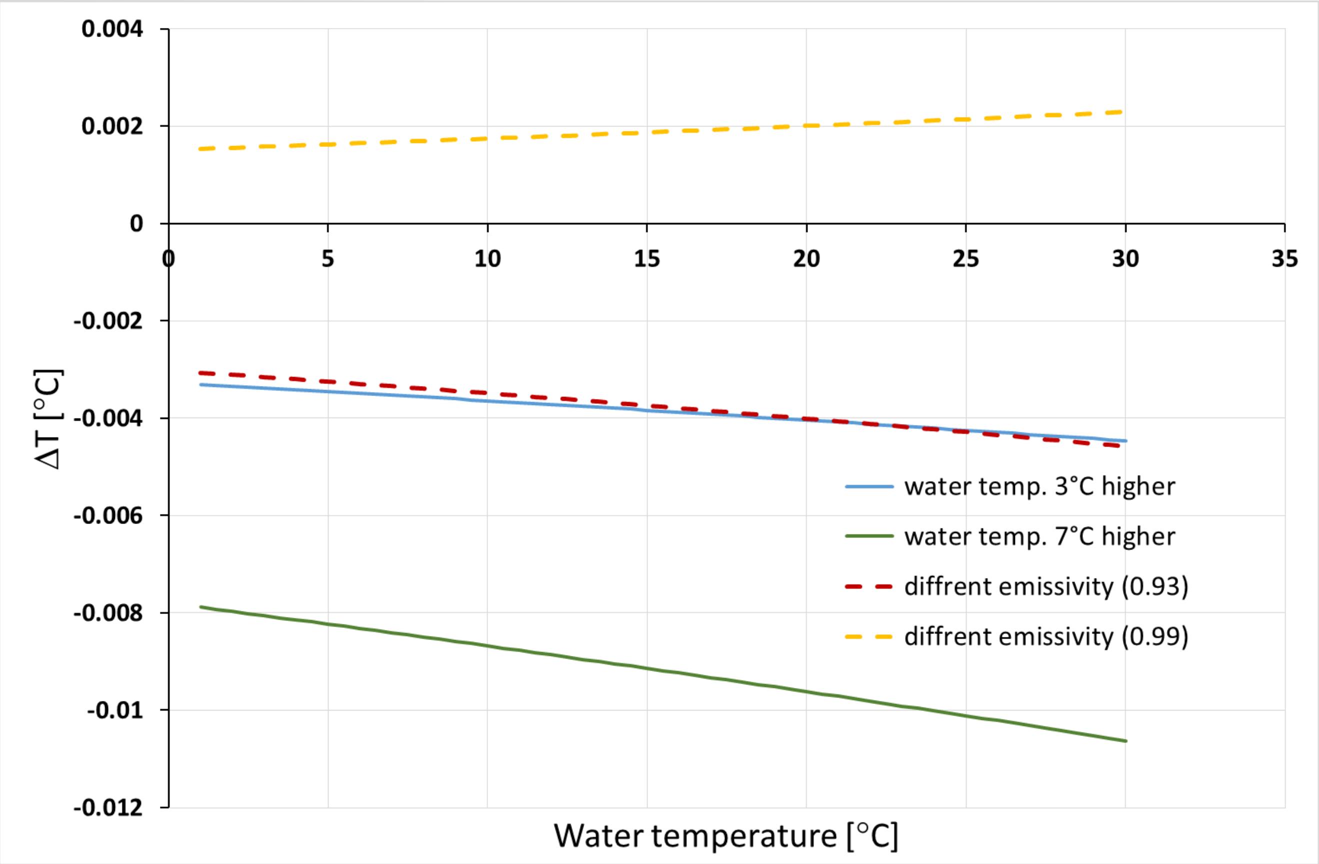
Evaporation and condensation



Evaporation and condensation heat flux for the Narew River case study calculated based on different formulae for the wind speed function.

Longwave back water radiation



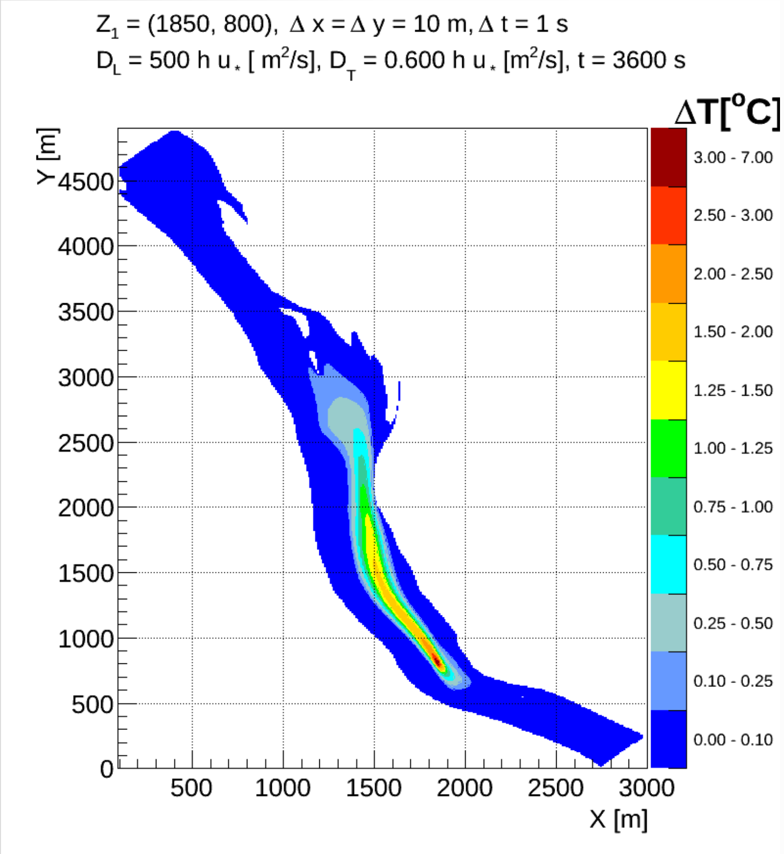
Difference in temperature change caused by long-wave back water radiation when the water temperate is 3 or 7°C higher than natural water temperature (solid lines) or when different water emissivity coefficients: 0.93 or 0.99 are used (dashed line).

Results after 3600 s

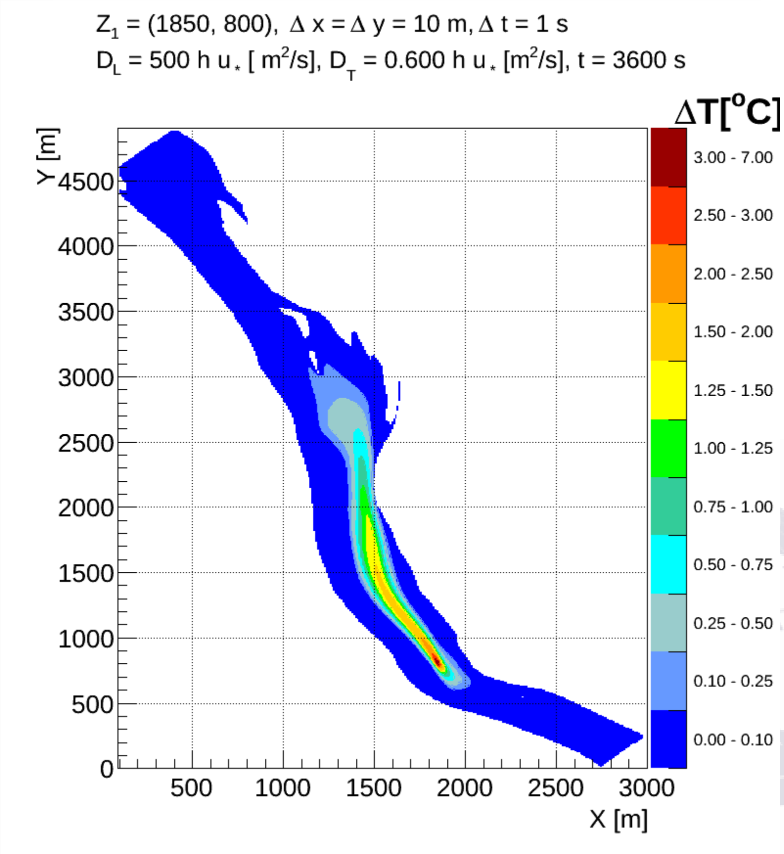
RivMix – Case study

Calculation of the temperature increase ΔT in the mid-field zone (in short time scale ~hours)

Without Q_A



With exemplary Q_A



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Results after 3600 s

RivMix – Case study

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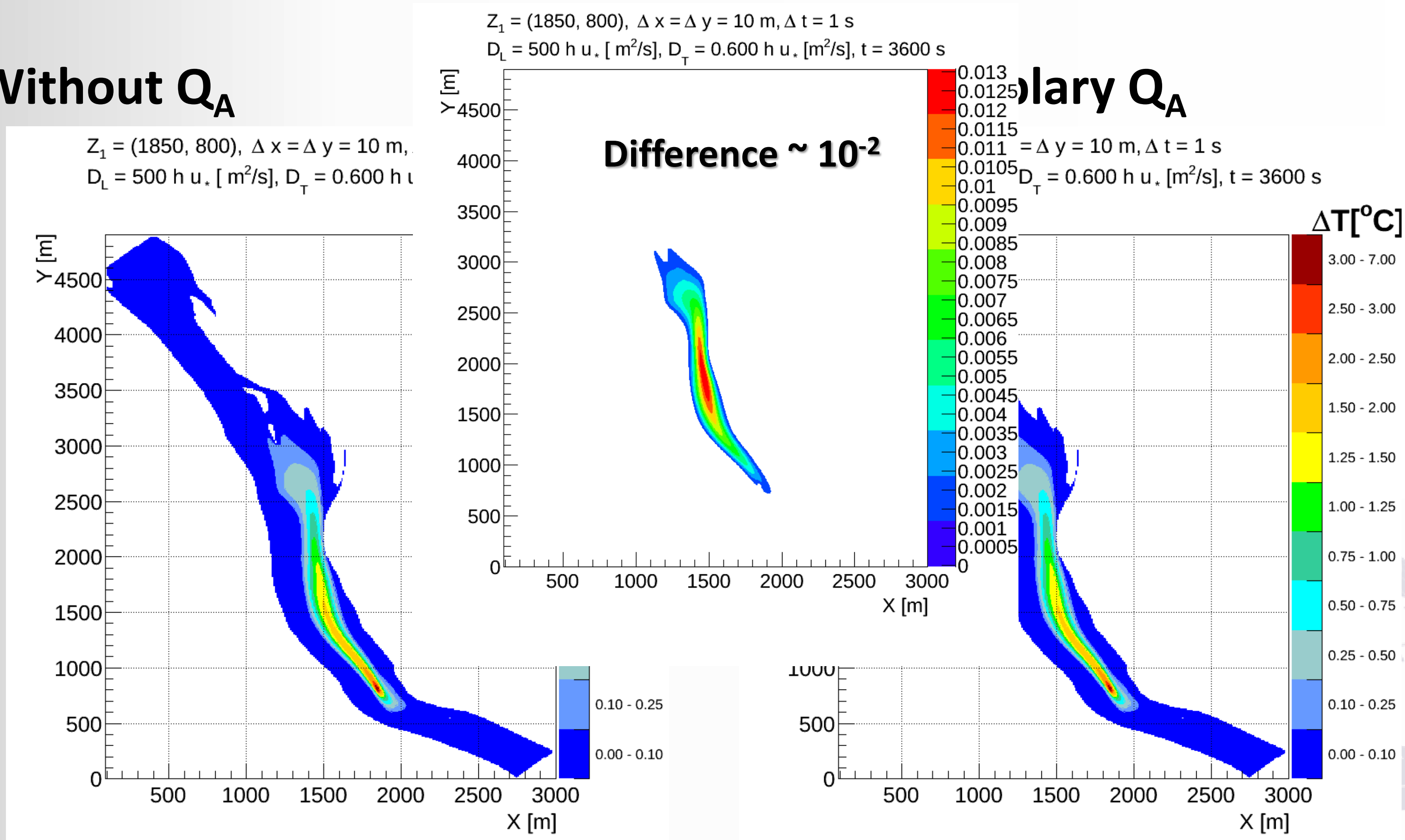
…lary Q_A



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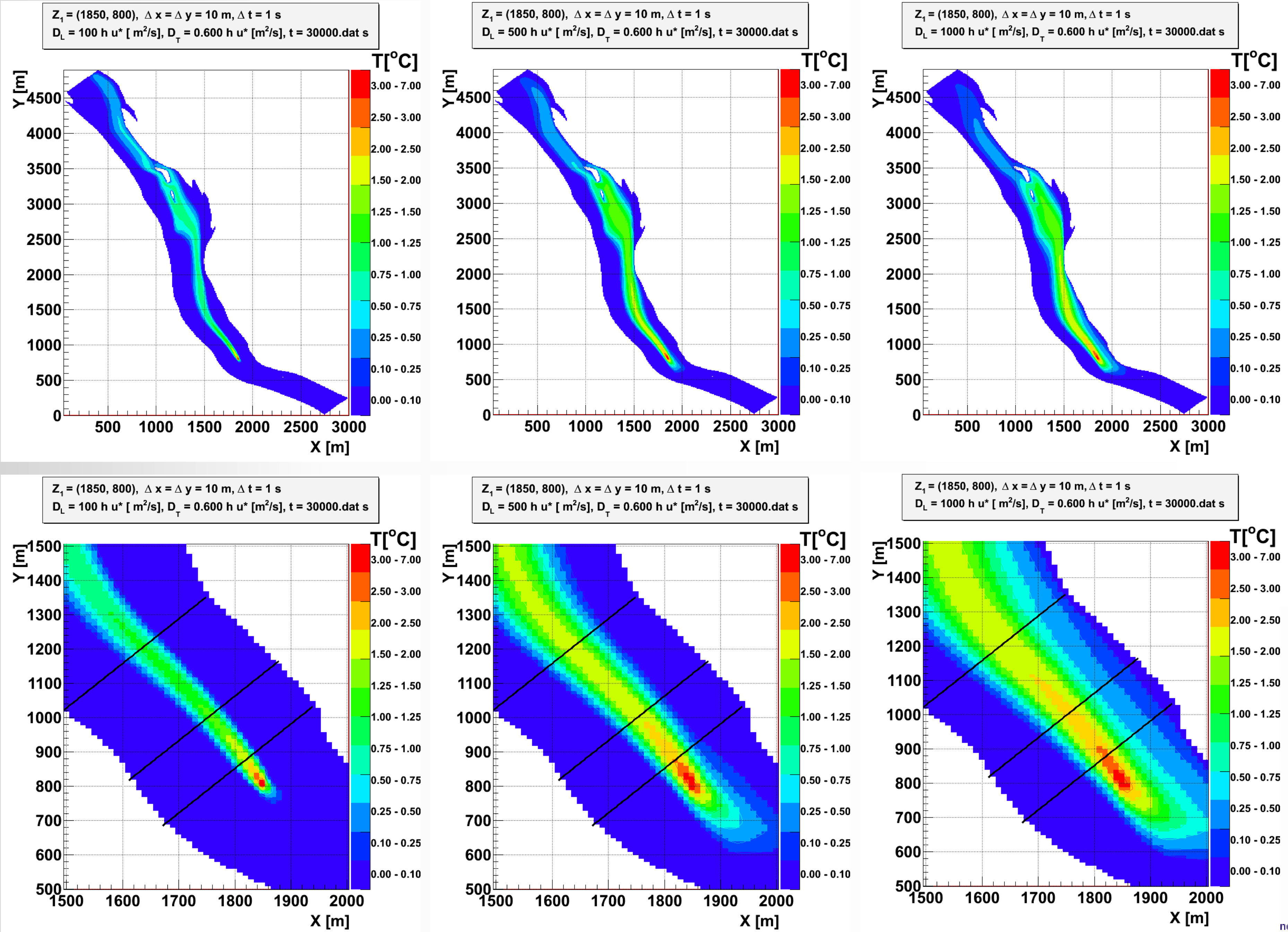
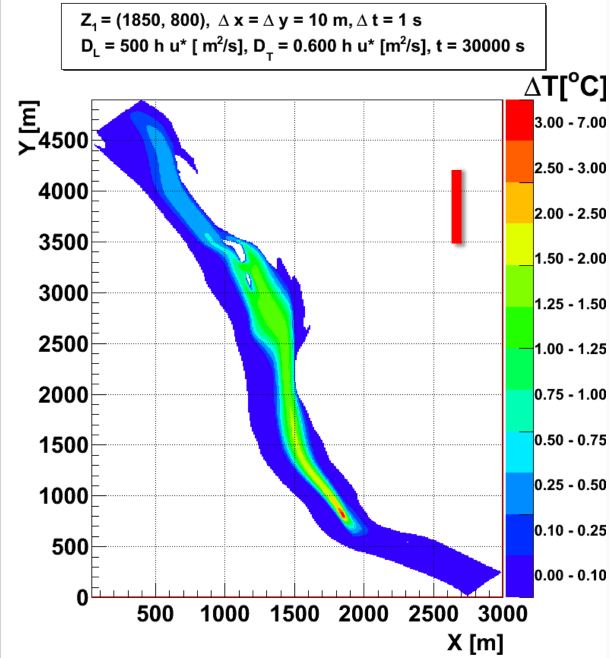
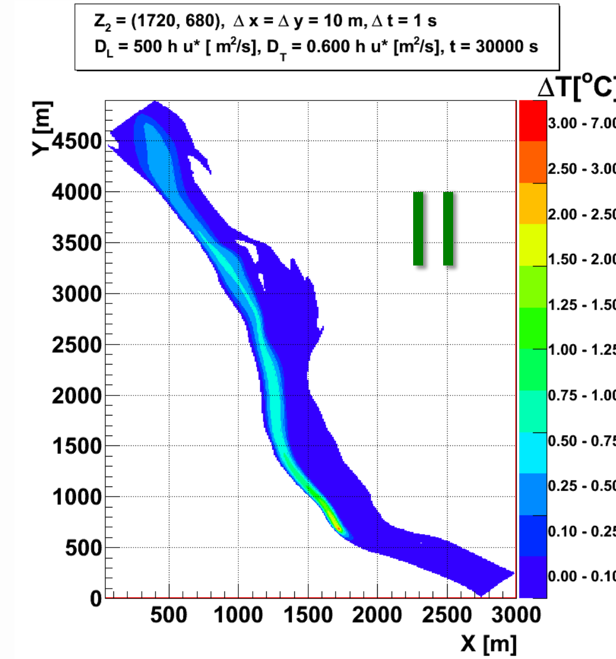
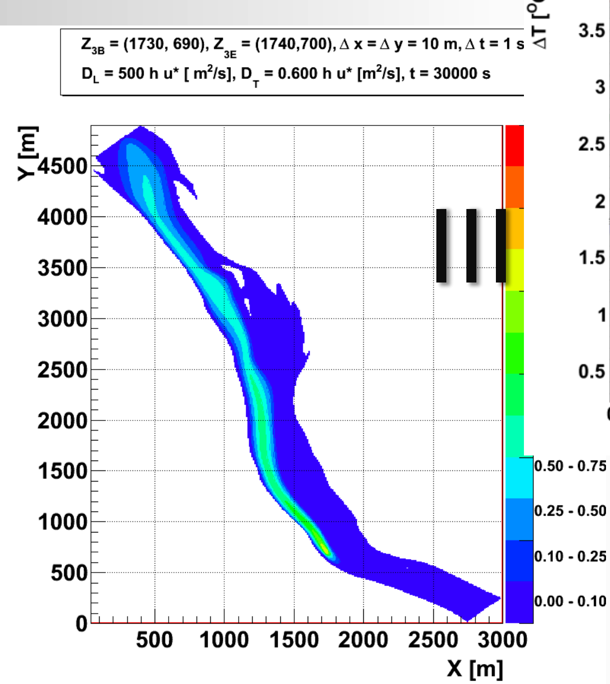
Results for different way of computation of dispersion coefficients

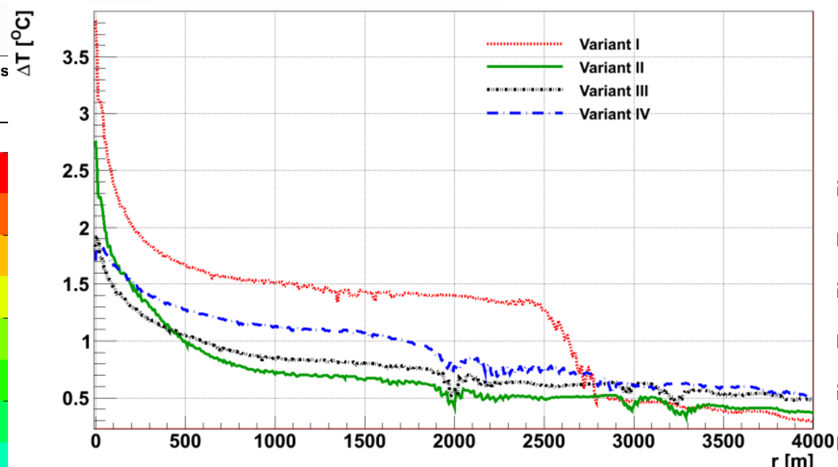


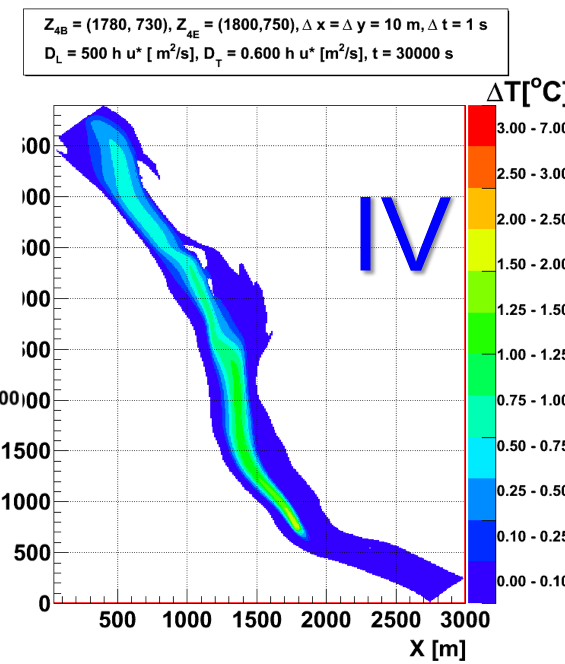


Results for different variants of heat discharge

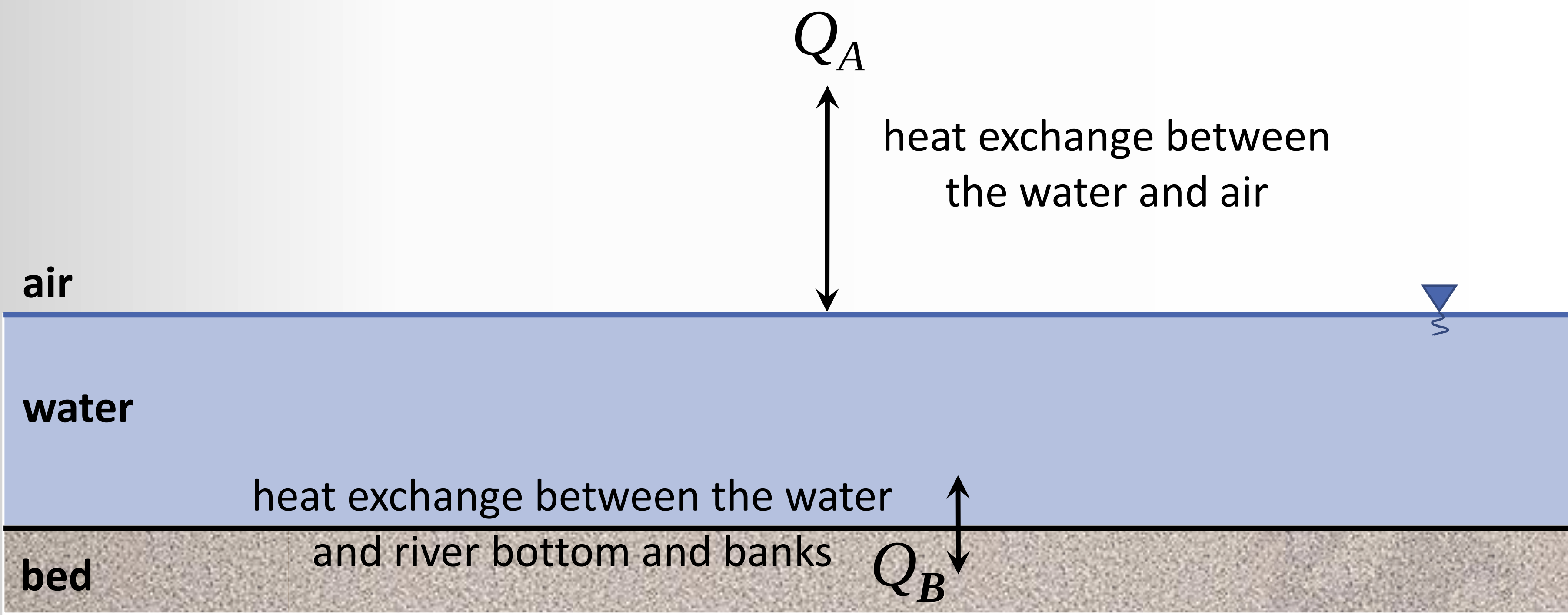








Heat exchange between a river and its environment



tributaries

rainfall

groundwater flows

biological processes

chemical processes

sediment

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Conclusions

- The form of the source term very much depends on the considered case.
- **The decision which of the processes should be considered in the given equation must be made taking into account:**
  - **the process significance,**
  - **the temporal and space scale of the process,**
  - **and the availability of data necessary to calculate the heat exchange with suitable accuracy.**
- In practical applications, most of processes, especially if we are interested in the situation of water temperature changes following the introduction of thermal pollution to the river, can be neglected at short temporal and spatial scales.
- The situation is different if the time scale of the phenomenon is long and diurnal or seasonal changes are important.

See details: Kalinowska M. B., Rowiński, P. M., (2015). Thermal pollution in rivers – modelling of the spread of thermal plumes”. *Rivers – physical, fluvial and environmental processes*, Springer

DZIĘKUJĘ

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