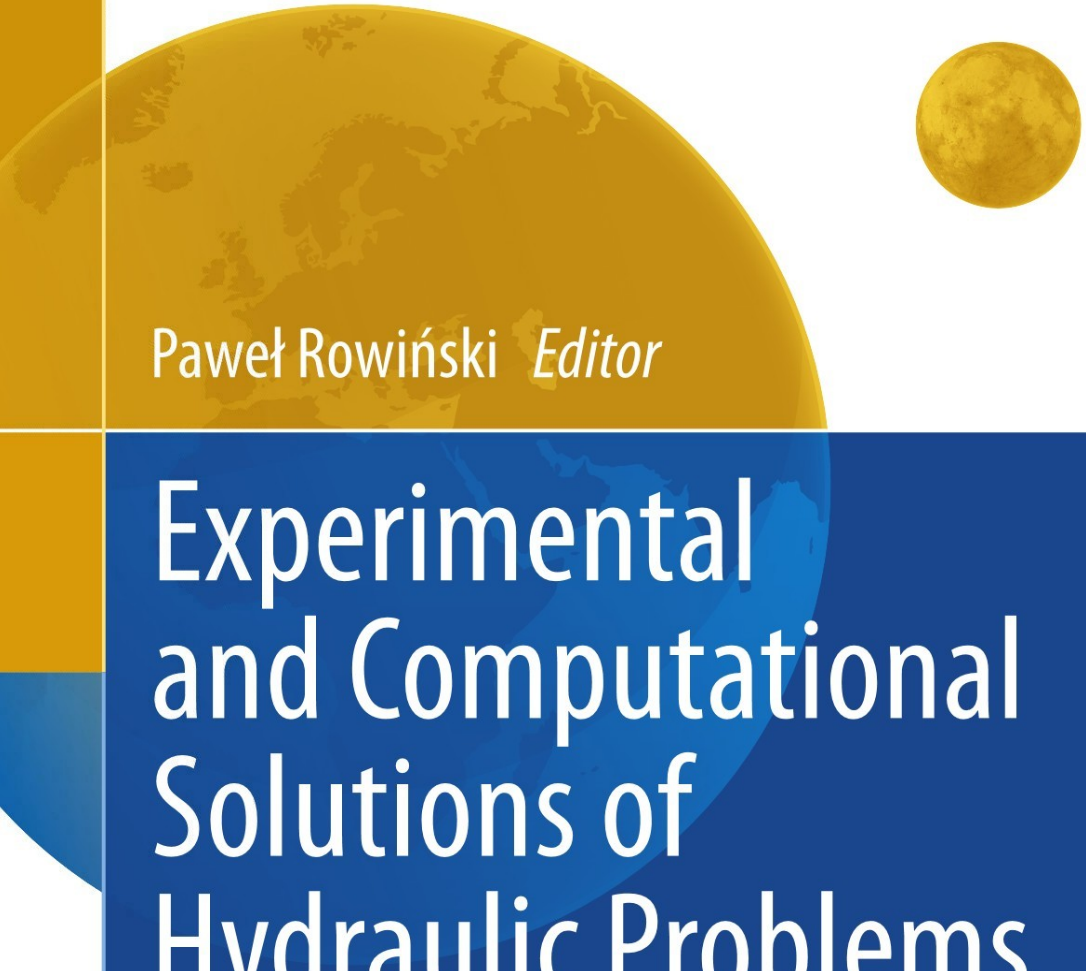

Paweł Rowiński *Editor*

Experimental and Computational Solutions of Hydraulic Problems

32nd International School of Hydraulics

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Editor

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Preface

This volume embraces a variety of research studies presented at the 32nd International School of Hydraulics *Experimental and computational solutions of hydraulic problems*. The papers that were accepted by the International Scientific Committee cover a wide range of subjects and research methods. They embody a mix of theory and practice, planning and reflection participation, and observation to provide the rich diversity of perspectives represented at the conference.

As is often the case, speakers had limited time in which to present their work at the conference and so the papers contained in this volume showcase the details of their research, approach, and outcomes. The authors represent a continuum from those with a record of research history in hydraulics up to those who have only very recently started to explore in this area, each with the benefits of their unique perspective. Particularly important to this volume is the invited comprehensive papers prepared by the internationally recognized indisputable authorities in particular fields of hydraulics. The keynote speaker at the meeting was Professor Donald W. Knight, whose research career over the years was associated with the Department of Civil Engineering of the University of Birmingham, United Kingdom. He prepared an excellent overview of hydraulic problems related to flooding. Professor Subhasish Dey from the Department of Civil Engineering, Indian Institute of Technology, India, together with S. K. Bose and O. Castro-Orgaz discussed the problems of hydrodynamics of undular free surface flows. Two Italian noble researchers highly enriched both the conference and the book: Professor Roberto Gaudio from the Soil Protection Department "Vincenzo Marone", University of Calabria (with coauthorship of S. Dey) with his contribution on the basic question of the universality of von Kármán's constant κ, and Professor Andrea Marion (with coauthorship of M. Tregnaghi) from the Department of Hydraulic, Maritime and Geotechnical Engineering, University of Padova, with his paper on novel methods of studying of incipient motion of sediment grains in open channels. A vision paper presenting research trends in the studies of aquatic ecosystems was provided by Professor Vladimir Nikora from the School of Engineering, University of Aberdeen, United Kingdom. The school has also ambition to raise very practical questions and the contribution of Professor Artur Radecki-Pawlik from the Department of Water Engineering, Agricultural University of Cracow in Poland went along such a line by discussing the issues related to construction and exploitation of rapid hydraulic structures in Polish rivers.

The International School of Hydraulics was also an occasion to celebrate **50 years** of pioneering work and role in shaping Polish environmental hydraulics by an extraordinary scientist, Professor Włodzimierz Czernuszenko, and this issue constitutes the subject of the paper of myself and Monika Kalinowska.

This volume contains 30 papers prepared by authors from 12 countries.

The 32nd International School of Hydraulics took place at the Palace Łochów located in a picturesque valley of Liwiec River, an hour away from the capital of Poland, Warsaw. The Łochów Palace is a nineteenth century Palace and park complex. The location, central part of Podlasie, is a historical gateway to the East, the place where many different religions and cultures converge. That beautiful surrounding and nice informal atmosphere made the School a unique scientific event.

Paweł M. Rowiński

Acknowledgments

I would like to thank all those who contributed to the 32nd International School of Hydraulics *Experimental and computational solutions of hydraulic problems* and the resulting volume. Great appreciation is therefore due to:

- All the invited speakers (Professors Donald W. Knight, Subhasish Dey, Roberto Gaudio, Andrea Marion, Vladimir Nikora, Artur Radecki-Pawlik) for delivering their excellent lectures and providing critical inputs and suggestions during the School.
- The Chairpersons of the sessions: Vladimir Nikora, Steve Wallis, Ian Guymer, Roberto Gaudio, Monika Kalinowska, Robert Bialik, Artur Radecki-Pawlik, Andrea Marion, Donald W. Knight, Subhasish Dey, and Jarosław Napiórkowski, who led them with insight, wisdom, and humor.
- The reviewers of the papers, particularly Robert Bialik, Włodzimierz Czernuszenko, Monika Kalinowska, Janusz Kubrak, Wojciech Majewski, Marek Mitosek, Jarosław Napiórkowski, and Steve Wallis for preparing their in-depth reports ensuring sufficient quality of all the contributions.
- The members of the Local Organizing Committee (Magdalena Mrokowska, Monika Kalinowska, Anna Łukanowska, and Anna Zdunek) who ensured that the process and the program remained as planned and did so effectively and with the necessary degree of flexibility; and who helped to make the School the success it was.
- Appreciation is also due to Anna Dziembowska for language editing of all the papers.

A significant factor in the success of the School was the support received from the following sponsors:

- Institute of Geophysics, Polish Academy of Sciences
- Polish Academy of Sciences and its Committee for Water Resources Management
- The International Association for Hydro-Environment Engineering and Research, IAHR
- GeoPlanet: Earth and Planetary Research Center of the Polish Academy of Sciences

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Pioneering Works in Polish Environmental Hydraulics: The Flavor of World-Class Science

50 Years of Work of Włodzimierz Czernuszenko

Paweł M. Rowiński and Monika B. Kalinowska

Abstract Achievements of a noteworthy Polish scientist, Professor Włodzimierz Czernuszenko, in the context of international cooperation are presented herein. He was one of the initiators of the in-depth research in the emerging field of environmental hydraulics. He is well-known for his studies on turbulence in open-channels, heat and mass transport in rivers and quite recently on solid particles' transport in rivers from the perspective of two-phase flows. This chapter was prepared on the occasion of the 50th anniversary of his scientific work.

1 Introduction

It is hard to point what is the beginning of the scientific discipline named environmental hydraulics or ecohydraulics. Although the subject attracted the interest of the mankind over thousands of years ago with, e.g., Aristotle (384–322 B.C.) and Archimedes (287–212 B.C.), the history of ecohydraulics as a separate discipline is rather new and may be counted in decades only. In Poland those decades coincide with the transformation of the political system and the development of science has obviously been correlated with those political changes. It so happened that in the last century a fundamental knowledge of flow in open channels was built often almost simultaneously—in the West on one side and in the Eastern and Central Europe on the other. The knowledge transfer particularly from the communist bloc to the western countries was rather limited and the scientific

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community in the West was usually not well informed about deep studies on this side of iron curtain, allowing for the better comprehension of the flow of water and matter in rivers and canals. Therefore, establishing links between those two scientific communities was extremely important for the benefit of our scientific discipline.

Professor Włodzimierz Czernuszenko, widely acknowledged as the father of Polish environmental hydraulics (as understood nowadays) and arguably the most influential Polish hydraulician at the time of the explosion of West-East collaboration… has celebrated **fifty years** of pioneering work and role in shaping Polish hydraulics. It is the first major retrospective to honor this extraordinary Polish scientist, one of the first to bring the flavor of world research into Polish environmental hydraulics community.

Professor Czernuszenko is one of the Polish most accomplished and highly acclaimed hydro-environmental scientists. His research and discoveries have influenced the study of transport processes and turbulence in open-channels, making it possible to understand the physics of those processes and, ultimately, to model those processes computationally. To those who know him only by professional reputation, Professor Czernuszenko is a scientist whose work opens new doors and lights new paths of discovery within environmental hydraulics. To those who know him personally, he is an amiable, soft-spoken man with a sly sense of humor, a man who is modest about his accomplishments and generous with his knowledge, advice, and encouragement.

Włodzimierz Czernuszenko has built an international reputation particularly with his works on turbulence in open-channels, heat and mass transport in rivers and quite recently on solid particles' transport in rivers from the perspective of two-phase flows. This chapter aims to briefly look into his selected research studies and to show their influence on the progress in the hydraulic engineering field. Modern hydraulics is no longer confined within the narrow boundaries of specific fields of thoughts—researchers must cross frontiers and Czernuszenko created an excellent example of such thinking.

2 River Turbulence

Flow in open channels is mainly in turbulent regime. Therefore, understanding of this ubiquitous nonlinear phenomenon is crucial for understanding practically all problems of environmental hydraulics. Studying of this phenomenon in respect to river flow had to draw on the achievements of all those research giants like Kolmogorov, Oboukhoff, Monin, Yaglom (in the East) and Hopf, Heisenberg, Taylor, Prandtl, von Karman (in the West) but also earlier works of Navier, Stokes and Reynolds. One cannot forget those who knew how to use that knowledge in broadening the understanding of river flow—Yalin, Grinvald, Grishanin, Nikora, Nezu, Nakagawa, Rodi, Knight and many others. Among them undoubtedly was Czernuszenko, although his early works were mostly known only in Poland.

Czernuszenko's early works of the 1980s were at the forefront of experimentation on turbulence in free surface flows. Although there was already quite a material gathered in international literature (e.g., Grinvald 1974; Imamomoto 1975; Raichlen 1967; Schuyf 1966) concerning turbulence characteristics in open channels but they all were of a very initial character and every well-performed experiment at that time was of extreme value. Early understanding of turbulence phenomenon referred to Richardson's energy cascade process and to the Kolmogorov theory of locally isotropic turbulence. The first experiments on open-channel turbulence were usually designed to confirm those theories and to find relevant scales of turbulence. The first experiments went along a well-established scheme which allowed for various comparison studies. In those studies turbulent flow velocity at any point was treated as a random variable. Obviously, the behavior of this velocity can be described by probability density function, $p(u)$. Velocity measurements provide a time series of values recorded at time instants at regular intervals Δt. The considerations were restricted to stationary and ergodic random processes. For such situation, the probability density function (pdf) is invariant with respect to time and only one sample record over a sufficiently long time interval is needed to define the pdf and relevant statistical characteristics. Thus, all information about the turbulent velocity at a point can be obtained from one time series. The pdf and the statistical moments depend only on the magnitudes of the velocities measured at one point in the flow and not on the sequence in which those values occur. On the contrary, relevant correlation functions and energy spectra depend on the sequence in which those magnitudes occur. Reynolds stresses depend on the simultaneously recorded velocities in two directions at a point, but similarly to the pdf function they are independent of the sequence of values. An analytical expression for the pdf for turbulent flows is not easy to establish. Nevertheless, for most practical (engineering) purposes, the function can be characterized by statistical moments of different orders that can be obtained relatively easily from experiments. All up to the fourth moment have usually been determined in experiments in open-channels.

The very first laboratory experiments in Poland allowing to determine the basic turbulence characteristics were carried out in the straight open channel (Fig. 1) of a width of 175 cm and a length of 16 m (Czernuszenko and Lebiecki 1980). Measurements were taken for Reynolds numbers ranging from 7,000 to 42,000. The technique was to measure the instantaneous longitudinal velocity values with use of micropropeller—those values were averaged over 1 s time intervals. Measurements were taken in numerous points allowing to obtain spatial distributions of basic characteristics, among them turbulence intensity, autocorrelation and structural functions as well as spectral distributions of energy. Those—from today perspective—very simple measurements allowed to determine the scales of turbulence: Kolmogorov's micro-scale characterizing "small eddies" in which energy dissipation and macroscale characterizing the greatest eddies occurring in the flow. Moreover, the measurements enabled the calculation of turbulent mixing coefficients, energy dissipation rate of eddies and range of eddies satisfying "5/3 Kolmogorov law". Czernuszenko further worked towards improvement of the

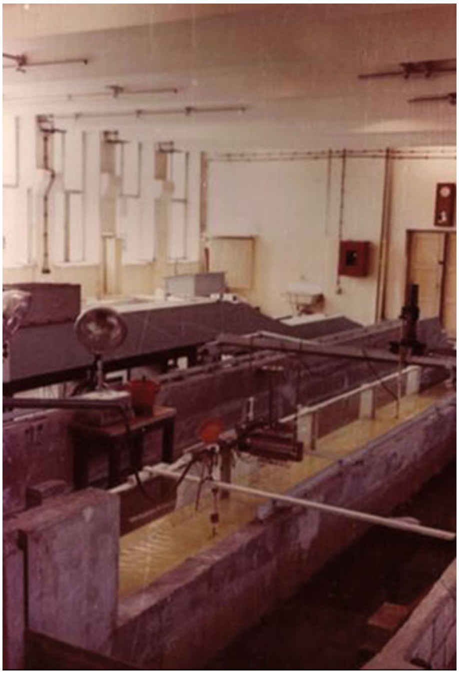


Fig. 1 Straight laboratory flume at the Institute of Meteorology and Water Management in the late 1970s

measuring techniques and ways of their interpretation and those studies encouraged him to go out of the laboratories to lead such measurements in the field. In the late eighties he organized field campaigns in Vistula River in the vicinity of Połaniec power station (three independent studies) (Czernuszenko and Lebiecki 1989) and a bit later in the Narew River in the reach behind warm water discharge from the electricity power station in Ostrołęka (Czernuszenko and Rowiński 1989). There were also studies performed in small streams and it gave an impulse to a long lasting collaboration with various groups of Prof. Vladimir Nikora (Fig. 2) at that time resulting in a common study of turbulence in (Nikora et al. 1993).

On top of providing invaluable data on turbulence structure in rivers, those studies were also extremely helpful for the verification of the fashionable jet models that were intensively built then. Together with gaining the experience in turbulence studies, Czernuszenko switched consistently to more and more complex situations and more difficult research questions. It is a common knowledge that rivers in flood are characterized by a compound cross-section (water overflows the banks to floodplains) and unsteadiness of the flow. The characteristics of turbulence are not well recognized in such a situation, even at present. In a compound channel one may suspect that additional flow resistance occurs due to an intensive momentum exchange between the deep main channel and the adjacent shallow floodplains. The flow structures that occur in rivers of a compound cross-section are very complex due to at least three mechanisms: boundary-generated turbulence, free shear layer turbulence and velocity fluctuations associated with perturbations in the longitudinal secondary flow cells. To make the considerations simpler, it is convenient to study the geometrical and temporal complexities in separation, i.e., to study the turbulence structure in a compound cross-section but at possibly steady state conditions and to additionally study turbulence under unsteady state condition. Czernuszenko has been recently involved in both of the above. Let us mention first his experimental investigations on the structure of turbulence in compound channels (Czernuszenko et al. 2007; Czernuszenko and Rowiński 2008a, b; Rowiński et al. 1998, 2002). Starting in the late 1990s, Czernuszenko and his collaborators initiated experimental studies in a compound channel. At the beginning, 1D experiments in a trapezoidal straight open channel with symmetrically complex cross-section with inclined side-walls were made (Rowiński et al. 1998, 2002). The originality of the approach consisted in simulating various hydraulic conditions by changing the roughness of floodplains. To achieve it, three series of experiments were performed—the first one was carried out in a smooth concrete channel (both main channel and floodplains), the second one was performed in a channel with rough floodplains and in the third test, plants (trees) growing on the floodplains were modelled by aluminum pipes placed on the floodplains. In that study it was confirmed that the vertical distributions of the local mean velocity can be satisfactorily described by logarithmic laws in two first variants of the experiment in the main channel and in the shallow part of it. The logarithmic law does not apply above sloping bank of the deeper section of the channel as well as in the experiment with high vegetation placed on the floodplains. Where the logarithmic law applies, the friction velocity and shear stress may be evaluated. In the central parts of the main channel and floodplains these values are in close agreement with the overall quantities obtained from the uniform flow formula. The model for the velocity distributions in the vegetated channel allows also for the evaluation of the friction velocity in such case. The longitudinal turbulence intensity variations in relations to depth turned out to be typical, i.e., the largest values occur at the channel bottom and the smallest ones at some short distance from the water surface. The intensity of turbulence increases significantly when the bed roughness increases and also at the interface between shallow and deep areas of the channel. Longitudinal sizes of the largest eddies were estimated with the use of autocorrelation functions and the hypothesis of "frozen turbulence". It was shown that in the floodplains these sizes are the smallest in the test with high vegetation (and the largest when the bed was smooth there). At some points the investigated spectral functions were characterized by the existence of an inertial subrange. They satisfied the Kolmogorov "-5/3" power law, which allowed for the use of the results of the theory of locally isotropic turbulence. In case of the vegetated channel, some additional energy supply except for the energy cascade is observed at the low frequencies, which is in agreement with the findings of other authors.

In the later studies, comprehensive measurements of *three-dimensional turbulent* velocities were carried out in the same channel (Czernuszenko et al. 2007; Czernuszenko and Rowiński 2008a, b). Tests were performed in a two-stage channel with smooth main channel bed made of concrete and rough floodplains

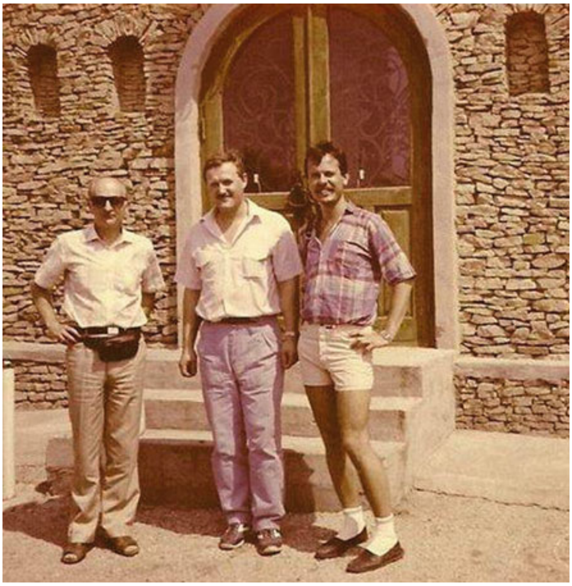
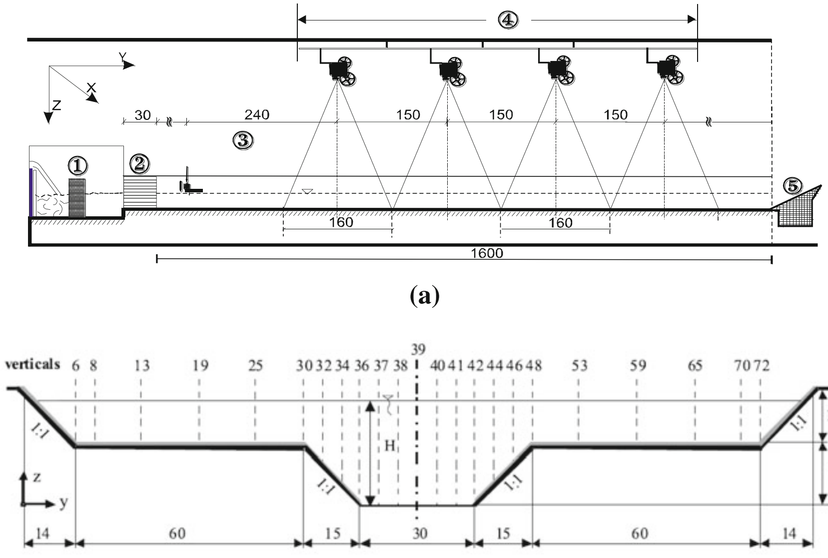


Fig. 2 Beginning of collaboration; Moldova, Kishinev, 1990; from the *left* W. Czernuszenko, V. Nikora, P. Rowiński

and sloping banks. Instantaneous velocities were measured with use of a three-component acoustic Doppler velocimeter. On top of determining traditional characteristics of turbulence, the main aim of the study was the recognition of structure of the Reynolds stresses in turbulent open channel flows. Particular attention has been paid to the bursting events such as ejections and sweeps. The bursting phenomenon occurs originally near the buffer layer and then shows a coherent or organized flow structure during its convection process. The probability density distributions of the turbulent velocities were measured at different distances from the bed in the main channel and also above inclined walls. In the main channel the lateral turbulent velocity is seen to follow the normal Gaussian distribution more closely than the remaining two components. Above the inclined walls all distributions turned out to have larger skewness. The probability density distributions of correlations between velocity fluctuations were also calculated. These distributions have long tails and sharp peaks and they fit the theoretical distributions very well. The structure of instantaneous Reynolds stresses was analyzed by quadrant technique with the arbitrarily chosen threshold level. It has been shown that the largest contribution to turbulent stresses comes from the second quadrant (ejection) and the fourth quadrant (sweep). The basic temporal characteristics for quadrant events like the average and maximum time for zero hole size have been determined in the study. Calculations of maximum duration time for all events reveal that those times are larger for even quadrants than for odd quadrants. The same channel was used much later for the studies of the migration of floating particles by means of an image processing technique (see Fig. 3). That work allowed to obtain Lagrangian characteristics in respect to the solid particles transported in a two-stage channel in turbulent regime (Rowiński et al. 2005). One



(a)

(b)

Fig. 3 **a** Scheme of the laboratory setup for the video tracking of particles in a compound channel (*1*—spillway; *2*—flow soothing pipes; *3*—particles' batcher; *4*—system of four digital cameras, *5*—net particles catcher). **b** Scheme of experimental cross-section (Rowiński et al. 1998, 2002)

should also note a very detailed 3D turbulence study that Czernuszenko performed together with Edward Holley (Fig. 4) for the data obtained in a rectangular flume channel (Fig. 5) at the University of Texas at Austin (Czernuszenko and Holley 2007). This is a marvelous, very detailed description of how to deal with such experiments and can with no doubts be recommended to students and young researchers—almost as a cook book for turbulence investigations.

Another issue related to hydraulic conditions under flood is associated with the flow unsteadiness. Czernuszenko's attempt was to fill the gap in interpreting the turbulence characteristics when the stationarity of the investigated random field $u(x, t)$ is violated. We do realize that most intensive transport processes in rivers occur during the passage of a flood wave. They strongly depend on turbulence characteristics so this challenge sooner or later had to be undertaken. An original study was designed to investigate the fluctuating velocity time series during the passage of two various flood waves generated on a lowland river (Wilga River) in central Poland and it was one of the first studies of that kind worldwide (Rowiński and Czernuszenko 1998a, b).

The statistical characteristics of the recorded time series were evaluated with the use of the discrete Fourier transform. It was observed that the horizontal turbulent intensities are larger in the rising branch than the ones in the falling branch of a flood wave. Surprisingly, the damping of turbulence is evident during

Fig. 4 Prof. Czernuszenko with Prof. E. Holley and his wife, Austin, 2002

Fig. 5 View of rectangular flume channel at the University of Texas at Austin (Czernuszenko and Holley 2007)

the passage of a flood wave and the degree of this damping is larger when unsteadiness parameter is larger. The studies performed during the passage of a flood wave led to yet another important result (Rowiński et al. 2000). A method of evaluation of time-dependent friction velocities was proposed and it made use of classic St Venant equations of motion. The key observation was that thus obtained friction velocities significantly exceeded the values obtained from the traditional uniform flow formula. This method gains more and more advocates nowadays (see, e.g., Shen and Diplas 2010; Mrokowska et al., this volume).

Experimental work was not the only approach that attracted Czernuszenko to work upon understanding of turbulence phenomenon. In 1994 a short monograph on modern mathematical models of the processes of transport and pollutant mixing in rivers was published (Czernuszenko and Rowiński 1994) and it turned out to be the first attempt in Poland to use two-equations turbulence models for open-channel flows. That study was also the first to discuss numerical problems with solving depth-averaged Reynolds equations in its k-ε version. A byproduct of that study was the ability to collaborate with leading research centers dealing with modeling of turbulence flows. Czernuszenko took special advantage of the gained experience in turbulence modeling a few years later. Together with his American colleagues he used a three-dimensional computational model, solving Reynolds equations with the k-ε turbulence closure to simulate the flow field in an open-channel near a side-discharge channel (Jia et al. 2002). It was a successful attempt showing the usefulness of the model for simulating 3D recirculating velocity field and it compared well with experimental results. In another paper (Czernuszenko and Rylov 2000), this time together with the researcher from Russia Alexey Rylov, he proposed his own model consisting in the generalization of the old Prandtl mixing-length hypothesis for 3D flows. That generalization consists in transition from scalar mixing length to mixing length second rank tensor. It turned out to be a very useful tool allowing for the calculation of the mean velocity distribution in non-homogeneous turbulent flows. This model has been used in different situations, also for compound channels (Czernuszenko 2001) and is successfully applied up to now (see Czernuszenko and Rylov, this volume).

His international reputation in modeling of open-channel flows led him to chair in transferring the state-of-the-art research and management tools and computational models in the areas of water resources and environmental engineering from National Center for Hydroscience and Engineering to Poland (see Altinakar et al. 2005) within a unique so-called US–Poland Technology Transfer Program financed by US Agency for International Development (Fig. 6). Actually with that institution—NCCHE in Mississippi (USA) Czernuszenko was specially connected—he has lectured there for almost 4 years starting in 1991.

There is one more modeling issue that should be noted as one of basic Czernuszenko's concerns. He has been always interested in searching for simple methods that could be useful for engineers. For example, when studying turbulence characteristics of open-channel flows Czernuszenko has not forgotten basic questions related to classic Prandtl velocity distributions. He has been keen to find relevant parametrization of the logarithmic law for the description of the velocity

Fig. 6 Ceremony of signing the *US–Poland Technology Transfer Agreement* in Warsaw, Poland, in November 5, 2002. From *left* to *right* (*back row*) Prof. M. Altinakar, Prof. Sam Wang, Prof. A. Clark, Prof. K. Rybicki, Prof. Z. Kaczmarek, Prof. W. Czernuszenko; (*front row*) Prof. C. Staton and Prof. B. Ney

profiles as a function of easily measurable variables (see, e.g., Franca and Czernuszenko 2006). As far as we know, this issue has been niggling him all the time and we expect solutions to this problem that will be beneficial for everybody in the field soon.

3 Mass Transport in Open-Channels

Rivers have always been the recipients of various kinds of pollutants resulting from human activities coming from domestic sources, industrial or agricultural effluents, or mining process waters. Over the last two centuries, since the age of industrialization, the massive increase of industrial production accompanied by the growth of large urban populations has led to severe water pollution problems in many rivers. Nowadays, the description and forecast of man's impact on water quality constitutes a key problem especially in well-developed countries. This problem receives an increasing attention of the public, politicians, decision makers nowadays. People have to answer how to achieve any given level and pattern of water quality, in particular watercourses and also how to mitigate the catastrophes that are inseparable elements of civilization. Czernuszenko has been always—throughout his career—part of the discussion and actually he was the initiator of numerous research trends in broadly understood water quality studies. Long lasting research in this subject matter of himself and of the entire team of the Institute of Geophysics PAS and strong international working tights led in 2005 to the preparation of the international monograph (Czernuszenko and Rowiński 2005) which was actually also a kick-off for intensive collaborative studies in the field that started afterwards. But for Czernuszenko all the story started in the 1960s.

In the second half of the twentieth century, as a result of the rapid development of industry, the need for environmental protection began to raise public awareness in Poland. Many new problems appeared in open channel hydraulics requiring a quick solution. One of the major problems was the description of mass transport of various types of substances discharged into surface waters affecting water quality. Meeting the needs of those times, Professor Czernuszenko put these problems in the mainstream of his scientific work. Most of his publications (including the first ones: Czernuszenko 1968, 1971, 1973a, c, d) and both his PhD thesis: "Mass transfer in the open channel flow" (Czernuszenko 1973b) and his habilitation based on the monograph "Dispersion of Pollutants in Rivers and Channels" (Czernuszenko 1983), all are dialing with them. Numerous of his works related to the mass transport processes (e.g., Czernuszenko 1983, 1987a, b, 1990, 2000a, b, 2001; Czernuszenko and Rowiński 1994) have become a great source of knowledge in the field of hydraulics. His publications (both in Polish and English) systematize the knowledge of pollutant transport in rivers and open channels. Complicated mathematical descriptions of the transport process are presented carefully and accurately, but in clear way, thus enabling to use them not only by scientists, but also by engineers and students. To all newcomers starting their adventure with the transport of pollutants (especially unfamiliar with the language of mathematics) the articles: Czernuszenko (2000a, b) (in Polish) or Czernuszenko (1990) (in English, part of the Encyclopaedia of Life Support Systems EOLSS), should be particularly recommended. The articles deal with the modeling of transport and mixing of different pollutants. Different substances which mix well with fluid medium (like mass, heat or electrical current) can be treated as pollutants and their concentration could be described by similar conservation equation. The first article cited above begins with the basic definitions and shows how to receive the equation and how to use it for the description of the concentration field in the water reservoir. The next two articles are an excellent continuation of the first one. Mass transport equations are derived there and then simplified (averaged) to two and one dimensional domains. Basic transport mechanisms, like molecular diffusion, turbulent diffusion, advection and dispersion are discussed in details with a special emphasis put on the differences among the molecular diffusion, turbulent diffusion and dispersion coefficients occurring in the derived equations. We all realize how important is to properly understand and use those coefficients in both scientific and practical applications but at the same time we still observe a big mess in the literature and user manuals of computer programs in this respect. Czernuszenko's works put some order in this field and his works constitute an excellent source of reference.

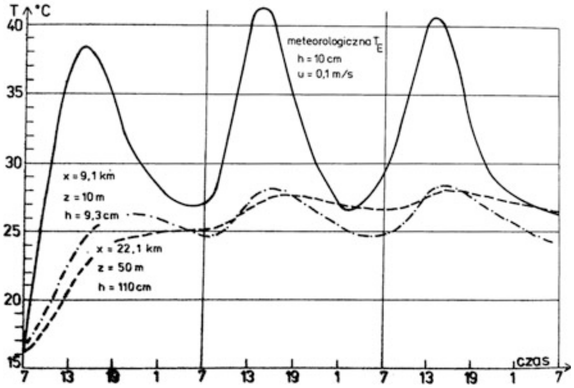


Fig. 7 Variation of natural temperature for 3-day water–air heat exchange, San River ($Q = 28.7$ m^3/s). Czernuszenko and Paradowska (1987)

One of the negative effects of industrial development have become thermal pollutions caused by discharges of heated water into rivers. From the works of Prof. Czernuszenko devoted to thermal pollution, particularly noteworthy is the paper: Czernuszenko and Paradowska (1987). That article deals with a two-dimensional spreading of thermal pollutants in a shallow river by means of a mathematical model taking into account the mechanism of convection, dispersion and heat exchange at the air–water (see Fig. 7) and soil–water interface. A substantial part of the paper is devoted to the comprehensive analysis of the air–water exchange with the description of all necessary empirical relationships. Also some examples of the applications of the presented mathematical model for rivers are discussed. Czernuszenko also took part in a series of experiments carried out on the Narew, Vistula and San Rivers, where three big Polish power plants: Ostrołęka, Połaniec and Stalowa Wola are located (see, e.g., Fig. 8).

River water is used for cooling purposes all over the world so the methods of analyses of the spread of a thermal plume are of extreme importance. The measurements of Czernuszenko and his collaborators included not only the cross sections, velocity profiles and two-dimensional (and sometimes even three-dimensional) temperature fields, but also the previously mentioned turbulence characteristics. The results are used and analyzed by Czernuszenko in several papers. He has also conducted a number of computational experiments. For example, the effect of the river bed profile on the temperature field was studied in details in: Czernuszenko and Paradowska (1987) and is presented fragmentarily in Fig. 9.

One of the major achievements of Prof. Czernuszenko was using the curvilinear (natural) coordinates system (Fig. 10) in the computations of spreading of pollutants in natural rivers. The lateral component of velocity greatly affects the mixing process, especially in natural, irregular, meandering rivers. At those times the measuring of this component or its calculation was extremely difficult and the use of the orthogonal curvilinear coordinate system allowed overcoming these difficulties (Czernuszenko 1986a, b, 1987a, b).

An important part of Czernuszenko's investigations were also related to the spread of pollutants in rivers over long distances. In such case, 1D approach is

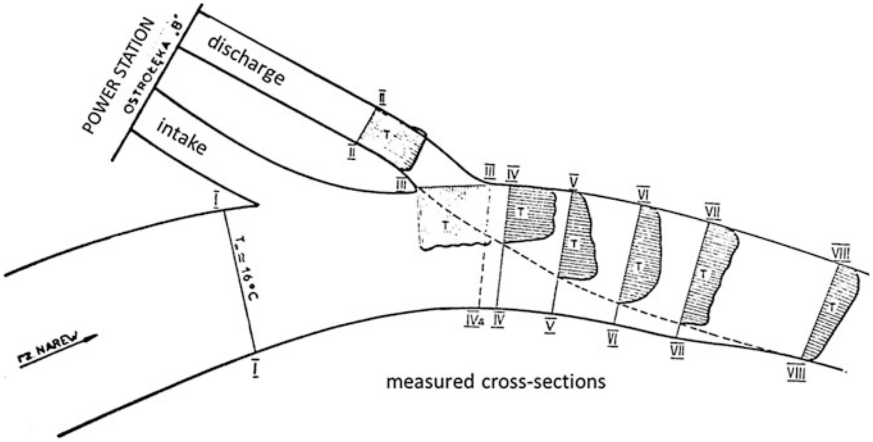


Fig. 8 Heated water jet behind the discharge from a thermal power plant in Ostrołęka (Narew River)—experimental results on the temperature field

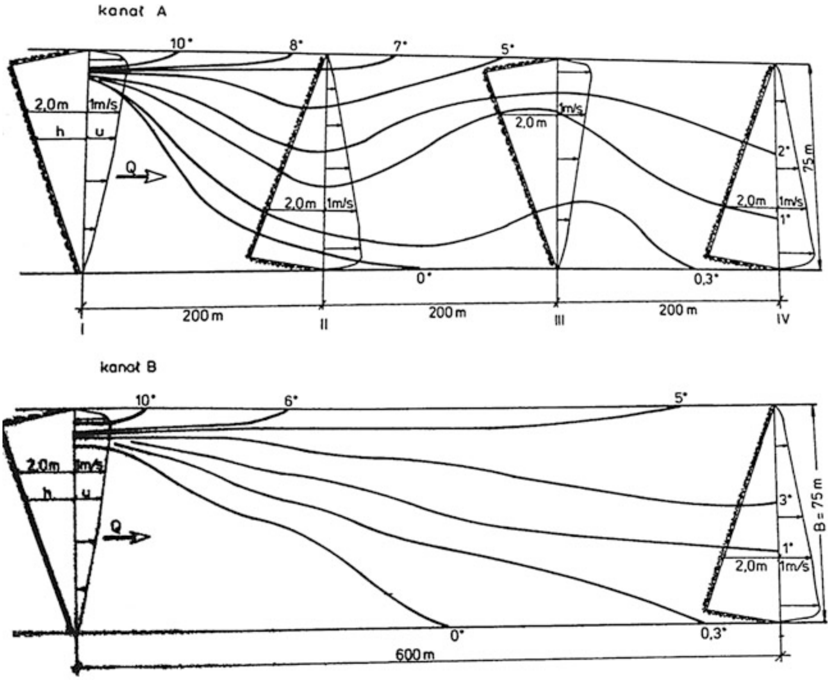


Fig. 9 Temperature distribution in two channels characterized by different bathymetries (Czernuszenko and Paradowska 1987)

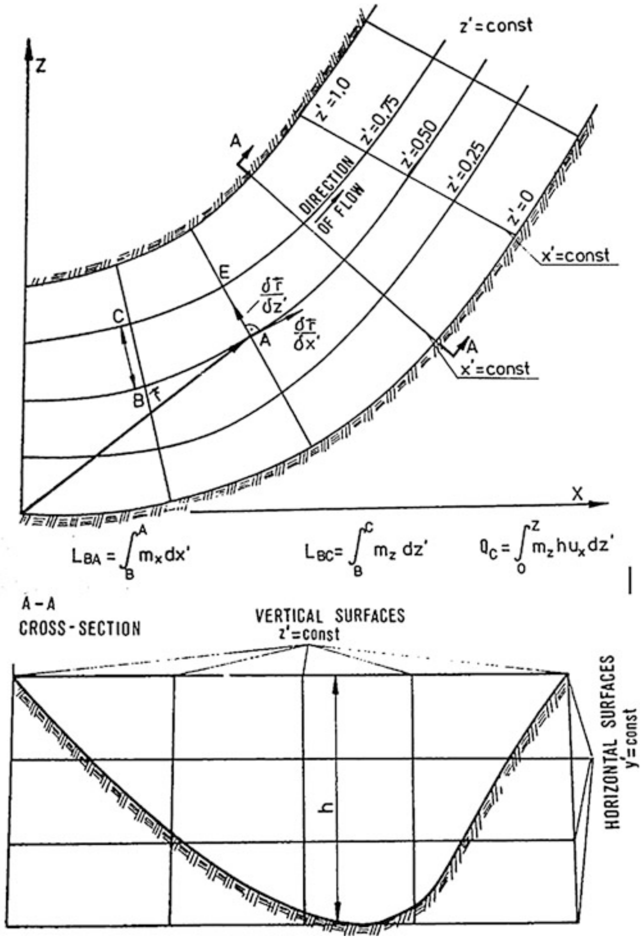


Fig. 10 Natural system of curvilinear coordinates for a river. m_x, m_z—the metric coefficients (Czernuszenko 1986a, b, 1987a, b)

sufficient (Sukhodolov et al. 1997). The 1D advection–dispersion equation has been successfully applied for many real cases; nevertheless, questions about its applicability arise very often. The tail of a solute tracer pulse is often more pronounced than can be accounted for by the traditional advection–dispersion model. A common method for simulating these long tails has been to allow for storage zones along the stream channel. These storage zones are assumed to be stagnant relative to the longitudinal flow of the stream and to obey a first-order mass transfer type of exchange relationship. Very often a quicker decrease of the concentration maximum than follows from traditional Fickian equation is observed. Also a nonlinear growth of the concentration distribution variance and dependence of the dispersion coefficient on time has been often manifested in experimental studies. The shift of the lower parts of temporal concentration distribution may be possibly explained by the dead-zone trapping and it motivated Czernuszenko to study a model taking into account this phenomenon. The dead-zone model has become increasingly popular for the calculation of the longitudinal dispersion of a solute in a river with irregular cross-sections and Czernuszenko's team was one of the first to study the model in details. This model is the reflection of the existence in the rivers of stagnant zones of water that are stationary relative to the faster moving waters near the center of the channel. The model results coincide well with experimental data (see Czernuszenko and Rowiński 1997; Czernuszenko et al. 1998).

Transport processes were treated by Czernuszenko from various perspectives. One way was to draw from the theory of two-phase flows and quite symbolically this is what ties the studies of the first doctoral dissertation that he supervised with the last one. At the beginning as an intermediate step towards the simulation of sediment transport and understanding of bed dynamics, Czernuszenko and Rowiński were interested in the determination of the paths of single grains in turbulent open channels or river flows (see, e.g., Rowiński and Czernuszenko 1999). In the early nineties the literature on sediment transport had led to major revisions in a view of turbulent transport of individual solid particles that was based on the equations proposed in the forties by Tchen. And the authors proposed a novel approach in comparison to other studies in literature. It is a common knowledge that the sediment grains may move in the form of rolling, saltation and suspension. The manner of their motion depends on many factors, like the position at which the particle initiates to move, its size, shape, density relative to the carrier fluid, as well as turbulent properties of the flow. In general, the way in which a particle moves is a direct effect of the role and significance of particular forces acting on a grain and also the variability of other solid particles concentration in its neighbourhood. It is expected that every mode of particles' movement should be described with the use of the same dynamic equations and this is what was achieved under supervision of Czernuszenko. When dealing with the particles contacting the bed, some supplementary model of a stochastic nature, responsible for the collision with solid boundary, was proposed. The proposed model included the term standing for the turbulent diffusion driven force and its main idea is based on the theory of turbulent flow of a dilute two-phase suspension derived from the first principles by Lee (1987), with whom Rowiński happened to collaborate that time. Czernuszenko was quick to realize the usefulness of the derived theory and he decided to look at it—the drift (diffusion) mechanism—from the perspective of mass conservation equation (Czernuszenko 1998). In sediment-laden flows with a concentration gradient the drift velocity arises as a result of nonsymmetrical turbulent fluctuations. Its existence is reflected in the proposed new model consisting in the mass conservation equation including three mechanisms—advection, diffusion and the drift.

This subject area came back in Czernuszenko's studies quite recently. Together with his last PhD student, Robert Bialik, he approached the problem again taking into account the new developments in other research centers. And as usually in