Paweł Rowiński *Editor*

Experimental Methods in Hydraulic Research

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Preface

Hydraulic research is developing beyond traditional civil engineering to satisfy increasing demands in natural hazards assessment and also environmental research. In such conditions, experimental methods draw from various areas of human activities and research, i.e., from physics, biology, chemistry, aerospace research, oceanic research, etc. Our ability to describe processes in nature rests on the observation and experimental methods as well as on theoretical basics of various disciplines. The current volume, being a result of the meeting that took place in Wiejce Palace in Poland during the 30th International School of Hydraulics, has an ambition of presenting a kind of state-of-the-art as well as ongoing research projects in which experimental methods play a key role. It is obviously the task that may be only partially fulfilled in one volume but definitely provides a valuable material for researchers and students involved in hydraulic studies all over the world. The authors from numerous laboratories in various countries guarantee a representative sample of different studies lying at the frontier of the field.

This book covers problems differing in scale, subject, used methods, and geographical location. Chapters have been prepared by the leading experts in the field as well as by young researchers from 11 countries from four continents. There were seven invited speakers at the meeting (but only six chapters were submitted to this volume), and they prepared relevant contributions based on their lectures. In fact, two comprehensive chapters deal with various aspects of sediment transport in rivers. The chapter of Dey provides an overview of the theoretical basis of sediment transport with a special emphasis put on the problems of entrainment in the streams characterized by loose boundary. Coleman treats the problem of sediment transport from the perspective of the measuring techniques allowing to investigate the dynamics of the riverbeds. Manson describes unique series of experiments in Iceland rivers pertaining to better understanding of stream metabolism. Two contributions deal mostly with laboratory techniques and the detailed physics of particle movement in open channels. Di Cristo provided a state of the art in particle imaging velocimetry and its applications in hydraulics. Ferreira concentrated more on revealing and comparing the applicability of laser Doppler anemometry (LDA) and particle imaging velocimetry (PIV) in the studies of turbulence in open-channel flows over mobile and armored beds and to scour mechanisms. Majewski discussed a case study related to the hydrodynamics of Lake Żarnowiec influenced by nuclear and pumped storage power plant. Other chapters in the book deal with a variety of subjects devoted to hydraulic engineering with special emphasis put on experimental techniques.

The meeting in Wiejce was a jubilee 30th School of Hydraulics, and therefore, a few words on the history of this event are relevant in this place. International School of Hydraulics (till 2003 a national event) has very long tradition – it was initiated in 1981 and took place without interruption each year. Throughout all that long 25-year period, it has been successfully organized by the Institute of Hydro-Engineering of the Polish Academy of Sciences. Starting from the 26th, the organization of International Events was taken over by the Institute of Geophysics, Polish Academy of Sciences. The 26th School took place at Goniądz in Biebrza National Park, the 27th at Hucisko (the Eagle's Nest) situated in the heart of Jura Region in southern Poland, and the 28th one at the Podewils Castle in a small town of Krag, the largest fifteenth-century Knight's Castle in Pomerania. Those Schools have been carried out under the auspices of the Committee for Water Resources Management of the Polish Academy of Sciences and International Association of Hydro-Environment Engineering and Research IAHR, particularly its Committee on Experimental Methods and Instrumentation. All events turned out to be a great success and gathered many researchers from various countries, among them the European leaders in the field of hydraulics. Starting from 2008, the International School of Hydraulics takes place every second year.

The next article, 30 Years of the School of Hydraulics, is an excerpt from the lecture of Professor Majewski, the head of 25 Schools, and it provides an overview of the long history of the School of Hydraulics.

There are a few individuals that have to be acknowledged herein. The 30th International School of Hydraulics, and consequently this book would not be possible without the dedicated work of the staff members Anna Łukanowska, Anna Zdunek, Monika Kalinowska, and Robert Bialik. Anna Dziembowska carefully checked the format of all submitted chapters, made various corrections, and assured good quality of English of all chapters of the book. Special thanks go to the members of International Scientific Committee of the School for their continuous support, namely, to Andreas Dittrich, Ian Guymer, Andrea Marion, Vladimir Nikora, Steve Wallis, and Anders Wörman. All chapters have been reviewed, and I am especially grateful to Włodzimierz Czernuszenko, Janusz Kubrak, Wojciech Majewski, Marek Mitosek, Jarosław Napiórkowski, Michał Szydłowski, and Robert Bialik who assured high professional standard of all contributions.

Institute of Geophysics, Polish Academy of Sciences Paweł M. Rowiński

30 Years of the School of Hydraulics

Introduction

Thirty years passed since the first School of Hydraulics was organized. This 30-year anniversary of School of Hydraulics generates both retrospections and outlooks to the future. In such a situation, two questions may be asked:

- Where are we going? Which means, what will be the future of the School of Hydraulics?
- Where we come from? What was the beginning of the School and how it developed till the present day?

Answer to the first question belongs now mainly to the organizers of the next Schools. I would like, however, to concentrate my presentation on the past of the School of Hydraulics. What was the idea of the School, how it was organized, what topics were discussed, and what can be regarded as achievements and what as failures.

Organization of Schools

In the beginning of 1981, the Committee on Water Resources Management of the Polish Academy of Sciences (CWRM PAS) decided to initiate the School of Hydraulics (SH) under the general heading *Contemporary Hydraulic Problems of Inland Waters*. This idea was to follow, the already operating, School of Hydrology – *Contemporary Problems of Hydrology,* which was also organized under the auspices of the CWRM PAS. The initiator of the School of Hydraulics was Professor Bolesław Kordas, chairman of the CWRM PAS. Wojciech Majewski from the Institute of Hydro-engineering (IH) of the Polish Academy of Sciences, at that time associate professor, was appointed as the scientific chairman and organizer of the IH.

The main aim of the SH was to create a forum for discussion and education in the field of inland water hydraulics including also hydraulic structures. The aim was also to improve the scientific and engineering level of hydraulics, understood in a very wide sense. The School meetings were planned to take place every year in September. It was expected that participants of SH will come from universities, technical and agricultural universities, research institutes, enterprises dealing with hydraulic engineering, and administration for water resources management.

Each School was devoted to a selected topic of inland hydraulics and consisted of lectures given by eminent specialists and presentations of the participants in the form of papers or communications. These included excerpts from doctor dissertations or habilitation thesis. It was envisaged to present during SH reports from international congresses, symposia, or seminars.

Each time, the School was organized in a different place and connected with a visit to interesting hydraulic structure during construction or operation. Assistance for organization of each SH was provided by a given institute or university, which had the opportunity to present its organization and scope of research.

The first SH was organized in Osieczany in September 1981. Professor B. Kordas, who was the initiator of the SH, died tragically several days before the School started.

The Initial Years of SH

The initial years were very difficult because of political unrest in Poland, which resulted in the shortage of funds for science and difficulties in food supply. The situation worsened in 1982 when the Martial Law was introduced. All this produced additional organizational difficulties. Fortunately, due to the involvement of many people, all these problems were overcome and SH was regularly organized every year. Organization and main topics of all 30 Schools are presented in Table 1.

Further information about SH (place of the School and visited hydraulic facility) are provided in Table 2.

School Organization and Proceedings

The only records that remained from the first Schools were short reports. There was no publication of proceedings. For the first time, full proceedings including papers were prepared from the V SH (1985). Next there was a book of abstracts of lectures and papers from the X SH (1990). Since 1991 (XI SH), proceedings including lectures and papers were published regularly as monographs of the Institute of Hydro-engineering. In general, these proceedings were published before each School. All papers were reviewed before acceptance for presentation.

Table 1 Organization and main School topics

Year	School number	National or international	School organizer	Main topic of the School
1981	I	N	IH	Hydraulics of hydraulic structures
1982	II	N	IH	Flow in open channels
1983	III	N	IH	Sediment transport and its modeling
1984	IV	N	IH	Modeling of thermal regime in rivers
1985	V	N	IH	Scale effects in physical models
1986	VI	N	IH	Problems of flow in rivers and conduits
1987	VII	N	IH	Sediment movement and unsteady flow
1988	VIII	N	IH	Contemporary problems of hydraulic research and methods of solution
1989	IX	N	IH	New trends in river training
1990	X	N	IH	Unsteady flow in open channels
1991	XI	N	IH	Modeling of the flow (field and laboratory measurements
1992	XII	N	IH	Influence of hydraulic structures on the environment
1993	XII	N	IH	Hydraulics of open channels
1994	XIV	N	IH	Rivers and water resources management
1995	XV	N	IH	Physical processes in river flow
1996	XVI	N	IH	GIS in hydraulics and water management
1997	XVII	N	IH	Hydraulic aspects of floods
1998	XVIII	N	IH	Extreme phenomena in hydraulics
1999	XIX	N	IH	Flow modeling in open channels
2000	XX	N	IH	Flow modeling in open channels (continued)
2001	XXI	N	IH	Modeling of flow in open channels
2002	XXII	N	IH	Hydraulic structures and flood protection
2003	XXIII	N	IH	Modeling of floods and sediment transport
2004	XXIV	I	IH	Hydraulic problems in environmental engineering
2005	XXV	I	IH	Hydraulic problems in view of WFD
2006	XXVI	I	IG	Environmental hydraulics
2007	XXVII	I	IG	Transport phenomena in hydraulics
2008	XXVIII	I	IG	Hydraulic methods for catastrophes
2009	XXIX	N	AU	Contemporary problems of river channels in view of WFD
2010	XXX	I	IG	Experimental methods and techniques in hydraulic research

N National School in Polish language, *I* International School in English language, *IH* Institute of Hydro-engineering, Gdańsk, Polish Academy of Sciences, *IG* Institute of Geophysics, Warsaw, Polish Academy of Sciences, *AU* Agricultural University, Kraków

In 1995, it was decided to create a logo for the SH. Several proposals of logo were presented by the participants. The best one, prepared by Marian Mokwa from the Agricultural University, was finally accepted. It exists in the form of two letters in a circle SH. They can stand for Polish abbreviation (Szkoła Hydrauliki) but also for the School of Hydraulics in English. This logo exists till the present day.

Upto 2003, XXIII SH, the proceedings were published in Polish. Only some lectures presented by foreign scientists were published in English with Polish abstract.

Table 2 Location of SH and visited hydraulic facility

School number	Location of School	Visited hydraulic facility
I	Osieczany	Dobczyce Reservoir (construction)
II	Stawiska	Hydraulics Laboratory of IH
III	Janowice	Czorsztyn project (under construction)
IV	Augustów	Augustowski Navigation Canal
V	Szklarska Poręba	Tailing reservoir Żelazny Most
VI	Władysławowo	Pumped-storage power plant and nuclear power-plant (under construction)
VII	Błażejewko	Jeziorsko hydraulic project (Warta River)
VIII	Płock	Włocławek hydraulic project and Hydraulics laboratory of Hydroprojekt Włocławek
IX	Straszyn	Hydraulic powerplants on Radunia River
X	Kobyla Góra	Kobyla Góra dam
XI	Kraków – Wola Zręczycka	Dobczyce Reservoir, Czorsztyn hydraulic project (under construction)
XII	Międzyzdroje	Harbour in Świnoujście
XIII	Szczyrk	Cascade of River Soła
XIV	Lesko	Meteorological Station Lesko, Solina Dam
XV	Wrocław Trzebieszowice	Wrocław Water Node
XVI	Grodno near. Międzyzdroje	Szczecin Lagoon
XVII	Sobieszewo	Mouth of Vistula River
XVIII	Zawoja	Reservoir Świnna Poręba (under construction), Czorsztyn hydraulic project
XIX	Frombork	Ostróda-Elbląg Navigation Canal
XX	Kraków-Ustroń Jaszowiec	Upper Vistula Waterway, Wisła-Czarne dam
XXI	Sasino	Lighthouse Stilo, Sand Dunes near Łeba
XXII	Lubniewice	Boat-lift Niederfinow, Germany
XXIII	Tleń	Hydraulic structures on Wda and Brda Rivers
XXIV	Jastrzębia Góra	Pumped-storage power-plant Żarnowiec
XXV	Debrzyno	Hydraulic power-plants on Radunia River
XXVI	Bartlowizna	Biebrzański National Park
XXVII	Orle Gniazdo	Poraj dam, Jura Krakowsko-Częstochowska
XXVIII	Podewil	Hydraulic power-plants on Słupia River
XXIX	Jałowcowa Góra	Waterway of Upper Vistula, Dobczyce Dam
XXX	Wiejce	

In 2002, the Institute of Hydro-engineering won a competition for the Centre of Excellence (CE) of EU. It was decided to include Schools of Hydraulics in 2003 and 2004 into the activity of the CE. This way, two subsequent Schools, XXIV and XXV, were organized as international. Additional funds facilitated the invitation of eminent lecturers from abroad as well as foreign participants. This way, SH got an international flavor with all presentations in English.

In 2004, Prof. W. Majewski completed his position as the director of the IH. The new director of IH was no more interested in organization of SH. It was decided to transfer the organization of SH to the Institute of Geophysics of the Polish Academy of Sciences in Warsaw. Paweł Rowiński, at this time associate professor, assumed the position of scientific chairman of the School. Three subsequent SHs were organized at the international level by the Institute of Geophysics. Proceedings of these Schools were published by Springer (in Acta Geophysica) and Publications of the Institute of Geophysics (Monographic Volumes). This ISH received good international reputation and support of IAHR.

Unfortunately, the small number of participants in the ISH from Poland resulted in a discussion in the CWRM PAS and it has been decided to organize SH one year as national and the next year as international. This way, the XXIX SH was organized at the national level by the Agricultural University in Kraków. Proceedings from this SH are in preparation.

Participants

Participants represented numerous universities of technology, agricultural universities, research institutes, design and consulting offices, engineering enterprises, and water administration boards. The number of participants varied from 36 (1981) to 76 (1995) and 85 (1996). The number of participants depended not only on the topic of the School but also on the financial situation of institutions sending their participants. There were participants who regularly attended SH, while some attended just one or two SHs. Over the first 25 SHs, there were about 150 participants who attended the School.

Schools were considered not only as a scientific forum, but also as a social and very friendly meeting leading to many long-lasting friendships.

Lectures, Papers, Communications, and Discussions

Lectures were longer presentations concerning selected subjects. Papers were submitted and presented by participants. These usually concerned the topic of the School; however, other interesting papers were also admitted. In the course of time, it has been decided to distinguish the presentations of participants as papers or communications. Introduction of communications allowed, especially young scientists, to present some of their studies, which were not yet completed. In order to encourage young scientists to present papers during SH, a competition for the best paper was established. This came into force in 1999. The special evaluating committee established during each SH took into account not only the scientific value of the paper but also the form of its presentation. The best paper was awarded with a diploma.

During the first SH, six lectures and ten papers were presented. In 1995, there were eight lectures and thirty papers. Foreign lecturers were Prof. H. Kobus from Stuttgard and Prof. P. Larsen from Karlsruhe. After each presentation, there was discussion in the form of questions and comments. There were also numerous informal discussions concerning various scientific and engineering problems.

During two SHs, a discussion on teaching of hydraulics was organized. From the experience of those who had lectures on hydraulics, it appeared that one of the most difficult problems for students to understand is hydrostatics.

Since 2004, the number of foreign lecturers considerably increased as well as the number of foreign participants. This way, the idea of the International School of Hydraulics was accomplished.

School Achievements and Drawbacks

One of the achievements of SH was the amount of scientific degrees awarded to the participants. We did not have exact record of the number of doctor degrees awarded to School participants. However, we have a record of doctor habilitatus degrees awarded to School participants during the years 1981–2004. This number is quite impressive and amounts to 41. These participants came from Kraków, Warsaw, Wrocław, Poznań, Szczecin, and Gdańsk. It is worth mentioning that 14 participants out of these 41 became professors. It is not possible to assume that this is the only achievement of SH; however, it can be regarded that SH provided some kind of stimulus.

A serious drawback during this time was the lack of international contacts. Participations in foreign conferences and seminars were very few. It is difficult to find out what was the real reason for this situation: the lack of funds, low scientific or engineering level of proposed presentations, or simply insufficient command of English.

Organization of International Schools in 2003 and 2004 by the Institute of Hydro-engineering was the first step to improve the situation. Continuation in this direction by the Institute of Geophysics with Prof. Rowiński as th chairman of ISH is a very valuable activity. Unfortunately, the number of Polish participants is not sufficient and should increase.

Problems Which Formed the Topics of SH

During consecutive years, the topics were gradually evolving from studies on various types of hydraulic structures to hydraulic model investigations, including measuring techniques and scale effects. Several hydraulic laboratories existed in Poland during the initial years of SH. They performed model investigations of newly designed hydraulic structures in Poland, but there were also hydraulic laboratories mainly for teaching purposes. Some studies were carried out to better understand various physical processes existing in open channel flow as, e.g., dispersion of pollutants.

Flow in open channels was considered not only as water flow but also thermal regime, sediment transport, or influence of ice cover was taken into account. These problems were investigated on hydraulic models and in natural conditions in the form of in situ measurements. Measuring techniques were gradually developing. Some problems began to be solved by means of mathematical models. These became more and more popular. Problems of unsteady flow in open channels were becoming very important, especially because of flood problems.

Problems related to hydraulic structures were rapidly decreasing due to the fact that only few new hydraulic structures were designed and constructed. However, the problems of the influence of hydraulic structures on the environment were still present.

When Poland entered EU in 2004, numerous new problems connected with hydraulics appeared. In 2000, the Water Framework Directive was established and Poland accepted its rules. In general, it is now possible in retrospection to state that SH always tried to follow problems which were important to science and engineering.

Conclusions

Looking back to 30 years of SH, which passed, it is possible to state that this yearly meeting of scientists and specialists in the realm of hydraulics fulfilled the aims, which were assumed when the School was established. In retrospection of 25 years when I had the duty and honor to chair SH, I would like to say that the School could not be regularly organized without involvement of many participants, who prepared papers, lectures, and also served as reviewers, organizers of study tours, or preparing publications. It would be difficult to mention all their names, because the list would be very long. Some of them unfortunately passed away.

I am very glad that the School of Hydraulics has assumed now an international character. I would like to wish Professor Paweł Rowiński and the organizing team from Institute of Geophysics further success.

Committee on Water Resources Management, Wojciech Majewski
Polish Academy of Sciences

Contents

Experimental Investigations of Sandy Riverbed Morphology

Stephen Coleman

1 Introduction

The innate creation of order out of randomness that is evident in nature both entrances and mystifies. In this regard, mobile beds of granular materials almost invariably arrange themselves into highly organised patterns, with trains of regular water-formed sediment waves ubiquitous on riverbeds and often found in geological strata. In a pragmatic sense, understanding of these intriguing structures is significant in terms of analyses and management of near-bed habitats, transport of sediments and attached micro-organisms and chemicals (e.g. nutrients, contaminants), and design of structures in the fluvial environment (e.g. Amsler and García 1997; Coleman and Melville 2001).

In order to provide insight into developments in understanding of fluvial bedforms, the historical progression of observations and measurements of sand-bed morphology is overviewed in the following, culminating in a summary statement of the recognised position at the start of the twenty-first century. Based on outstanding questions of bedform dynamics at that time, the subsequent sections highlight recent investigations of fluvial bedforms, particularly highlighting the development of instruments and experimental methodologies to enable progression in understanding.

1.1 Early Observations and Measurements of Sand-Bed Morphology

With mankind's love and utilisation of natural and formed waterways, there can be little doubt that the transport of sediment, and the intrinsically associated bedforms, has been observed and studied throughout the ages, in the founding societies in

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Mesopotamia, China, India, Egypt, and the Roman Empire, for example. Graf (1984) attributes the first basic scientific statements about loose-boundary hydraulics to the Italian hydraulician Guglielmini (1655–1710), with the French hydraulician duBuat (1734–1809) providing detailed observations of bedform mechanics, including "furrow" shapes, sizes, propagation speeds, and associated sediment motions.

In deference to the hydraulician's interest in observable bedform dynamics, geologists use bedforms preserved in stratigraphic records to infer details of historical currents and sedimentary environments. In this regard, de la Beche (1851) and Sorby (1859) discuss ripple marks formed by currents, including their orientation, shape, sizes, motion, and transport of sediment. Sorby (1859) notes that such structures "are so common that they cannot have escaped the attention of anyone who has carefully examined stratified rocks." Jukes (1862) also discusses ripple marks formed by currents, including their sizes and motions. He concludes that current ripples indicate "that the strength, velocity and mode of action of moving water in the old geological periods was precisely of the same kind and intensity as those with which we are familiar at the present day."

Efforts regarding observations of bedform dynamics in nature and through controlled experiments accelerated in the late 1800s. Raudkivi (1967) cites an expression for bedform celerity given by Partiot (1871) based on observations in the River Loire. Numerous field observations of ripple marks, including their sizes and their dynamics, are provided by Hunt (1882), with a principal focus on ripples occurring in oscillatory flows. Darwin (1883) also discusses the respective fine-sand ripples formed in uniform currents and oscillating flows. Of particular relevance to the present chapter, he describes early experimental observations of current-ripple sizes, shapes, orientation, growth, and dynamics, noting that Forel (1883) refers to bedwaves formed by continuous currents as dunes in summarising observations and his experimental studies. Deacon (1894) reports further observations of experiments regarding the orientation, shape, propagation speed, transport rate, and associated sediment dynamics for current ripples, and how these vary with increasing flow strength. At the turn of the century, Bertololy (1900) carried out studies of the formation of waves on a flattened creek bed, recording their simultaneous appearance over the whole bed, orientation, downstream migration, lengthening, and lateral uniting to form normal current ripples (Bucher 1919).

In a notable work, Cornish (1901), a student of Kumatology, describes observations of current-generated sand waves that are much larger than ripple marks, i.e. dunes in today's terminology. He comments that Reynolds (1891) noted the presence of these large tidal sand waves below low water in model estuaries, where the existence of such waves in nature had been overlooked, principally as they are out of sight, until the model results encouraged searches for them. Having sought out field sites evidencing these tidal-current sand waves under conditions favourable to examination, Cornish (1901) notes the shape, orientation, and variation with flow of these larger waves and provides measurements of lengths, heights, and migration rates. He also provides observations of sand wave growth, including inferences of bedform elimination (or coalescence as described in more recent works, e.g. Führböter 1983; Raudkivi and Witte 1990; Coleman and Melville 1994). Cornish (1901) goes further to offer a theory on the origin, growth, and decay of sand waves in currents, where these waves can appear suddenly and subsequently grow considerably, and they are mechanistically different to the smaller current ripples. He attributes the origination of sand waves to a form of deposition-scour wave (identified later by Inglis 1949; Raudkivi 1963, 1966; etc.), where the initial waves extend themselves laterally even more quickly than they grow vertically owing to near-bed fluid dynamics. Growth is suggested to be limited by a combination of the water depth and decreasing effectiveness of the lee vortex as the bedform grows. Cornish (1908) further discusses the sizes of current ripples, sand waves, and upstream-moving bedforms (antidunes in today's terminology).

Studies of ripples and larger sand waves to this time were based on observations and sparse manual measurements of sizes and migration speeds. In a novel approach, a sounding lead covered in tallow was used by Siau (1841a, b) to prove the existence of oscillatory-flow ripple marks at depths of up to 617 ft (Johnson 1916). 1910–1920 saw a notable increase in bedform measurements and experimental studies of bedform dynamics, and a consolidation of understanding of current-formed bed waves, notably through the German works of Blasius (1910) and Forchheimer (1914), and the works of Gilbert (1914), Johnson (1916), and Bucher (1919).

The study of Gilbert (1914), carried out with the assistance of Edward Charles Murphy, is recognised as a landmark experimental investigation (e.g. Bucher 1919; Kramer 1935; Kondrat'ev et al. 1959; Raudkivi 1967; Graf 1984). Although the primary aim of the study was to determine the laws governing bedload transport, the tests of sediment diameters of 0.3–7 mm involved bedforms from threshold conditions to antidunes occurring for supercritical flows. Gilbert (1914) provides detailed observations of bedform types, origination, growth, migration and speeds, sizes (and relations to controlling factors such as sediment and flow depth and speed), transport, shape and three-dimensionality, variation with discharge (including sizes, speeds, and the dune-plane bed and plane bed-antidune transitions), interactions (including coalescence, bedform dividing, generation on larger bedforms, and antidune cycling), and associated sediment dynamics (including related actions of turbulent structures). In regard to bedform types, Gilbert (1914) discusses dunes, plane bed, antidunes, and shoals, commenting that antidunes were earlier noted by Cornish (1899), and also Cornish (1908) and Owens (1908b) in the discussion and closure of Owens (1908a).

Bucher (1919) provides a review of the work to that time on the origin of ripples and related sedimentary surface forms. He discusses current ripples (conventionally parallel, but also rhomboid and linguoid, and having notable similarities to aeolian ripples in terms of characteristics and origins), meta ripples and sand waves (deemed a serious menace to navigation), related forms, and transitions between them. He summarises data on bedform sizes and speeds of movement, suggests formation mechanics (including a potential Helmholtz instability for dunes), and describes the orientations, anastamosing hierarchy, shapes and three-dimensionality, migration and speeds, sizes (including lengthening with time, and changes with increasing and decreasing velocity), transport, controlling factors (including flow depth, fluid viscosity and sediment size and density), and associated sediment dynamics (including interactions with near-bed flow structures).

A review of European hydraulic research regarding transportation by traction is given by Kramer (1935), who augments this with additional experimental results. In discussing this paper, Straub (1935) presents the results of recent North American experiments, providing measurements of ripple sizes and observations of ripple formation, shape, movement, and variation with flow velocity. Kondrat'ev et al. (1959) provide a later summary of research on the theory of sediment movement, including discussions and analyses of theoretical, experimental, and field investigations on the movement of sediment as bedforms. Regarding Russian experimental studies of bedforms up to that time, they particularly highlight the early work of Velikanov in 1923 and extensive investigations of Goncharov, Lapshin, Roborovskaya, and Pushkarev in 1935–1936. In terms of experimental methodologies, they note developing large-scale use of photography, high-speed motion pictures, and special emulsion drops in numerous experiments over the period 1936–1946 as turbulent flow structure was investigated in conjunction with bedform and sediment dynamics under the guidance of Velikanov. Kondrat'ev et al.'s summary of Russian experimental investigations finishes with the studies of Kudryashov and Znamenskaya in the 1950s. They conclude that most investigators to that time had ignored the internal flow structure and focused on determining empirical relations between bedforms and structureless-stream variables such as mean velocity, depth, slope, sediment diameter, etc. They also note that the wide variety of proposed relationships revealed the extent to which the nature of the interaction between stream and channel was still obscured. In terms of Russian field investigations of bedforms, Kondrat'ev et al. (1959) note the studies on the rivers Volga, Mologa, Luga, and Kemka over the period 1934–1935 in which bedform arrangements, sizes, speeds, transport rates, and superposition were linked to flow and sediment characteristics. They also put forward a theory in which bedform generation is linked to pressure variations at the bed surface and basic laws of oscillation.

Inglis (1949) reviews work on fluvial ripples and dunes carried out in India over the previous decade using sediments sizes of 0.2–19.4 mm. He provides observations regarding bedform types (principally ripplets, ripples, dunes, and sheet movement) and transitions between them, mechanisms of formation (including scour-deposition waves and viscous-turbulent sediment motions), controlling factors (including flow depth, velocity, discharge, sediment load, and sediment characteristics, with cohesion and grain coarseness limiting or preventing ripple formation), shapes and three-dimensionality, sizes, bedform superposition and elimination, hydraulic resistance, and associated sediment dynamics (including interactions with turbulent structures).

1.2 The Ultrasonic Depthsounder Revolution and Non-intrusive Measurements of Bed Dynamics

In 1956, the US Geological Survey established a significant research project to investigate roughness in alluvial channels. Because photographic recording and manual measurements of exposed bedforms after the draining of a channel could be misleading regarding the characteristics of dynamic bedforms, as could subaqueous measurements of the bed surface by mechanical probing (e.g. using point gauges), a sonic depth sounder was developed to allow the non-intrusive measurement of bed levels in shallow water. Measurements of dynamic bed-surface variations in space and time were readily obtainable using the new depth sounder and its relative the dual-channel stream monitor (Karaki et al. 1961; Richardson et al. 1961), from which dynamic data on bedform types, shapes, dimensions, and migration and transport rates could also be easily determined. This development served to revolutionise the measurement and analysis of dynamic subaqueous bed topography in the following decades, becoming the principal experimental tool of use and enabling landmark advances in understanding and description of bedforms (e.g. ASCE 1966; Guy et al. 1966; Nordin and Algert 1966; Ashida and Tanaka 1967; Crickmore 1967; Jain and Kennedy 1971, 1974; Wang and Shen 1980; Willis and Kennedy 1980; Nakagawa and Tsujimoto 1984; Bridge and Best 1988). Later studies used similar approaches for non-intrusive bed measurements that utilised different instruments, e.g. an infra-red probe (Richards and Robert 1986; Robert and Richards 1988) and a laser displacement meter (e.g. Nairn 1998; Coleman et al. 2003; Tuijnder et al. 2009).

1.3 Outstanding Gaps in Understanding and Recent Research

Despite the highlighted studies and advances up until the 1960s, and the significant efforts over the subsequent years to the start of the twenty-first century, ASCE (2002) observed that even then it remained difficult to give assured answers to basic questions such as how to characterise a dune-covered bed, including bedform shapes, sizes, three-dimensionality, and their statistical natures.

In the following, recent research is presented into conjecture that has been put forward regarding gaps in the understanding of fluvial bedforms. In each case, the postulated understanding is outlined, and then experimental investigations involving the writer that test the hypotheses are described. With this approach, it is intended that the use of developments in instrumentation and experimental methods to gain insight into longstanding research questions will be highlighted, along with resulting progressive advances in understanding.

2 Bedform Generation

The generation of bedforms from plane-bed conditions is typically attributed to one of three phenomena: (a) turbulent fluid motions, (b) instability of the fluid-sediment flow system when perturbed, and (c) granular transport mechanics. Through significant research efforts, there has been a wide spectrum of theories developed, with all of these theories still presenting unresolved inconsistencies. Postulated theories are discussed below along with investigations designed to test the hypotheses and resulting findings.

2.1 Turbulent Fluid Motions and a Viscous-Fluid Flume

As turbulence is ubiquitous in natural water flows, it is reasonable to assume that turbulence is closely associated with fluvial bedforms (e.g. Velikanov 1955; Kondrat'ev et al. 1959; Jackson 1976). Yalin (1992) ascribes the formation of alluvial dunes and bars to bursting processes associated with the turbulent nature of the flow. Raudkivi (1997) also proposes that the initiation of ripples can probably be ascribed to turbulent bursting processes that exhibit certain orders. Yalin and da Silva (2001) note that no periodic bedforms, including ripples and dunes, occur in laminar flows, thereby inferring the crucial role of turbulence in bedform origination. Challenges to the concept that bedforms are turbulence generated include that the principally random nature of turbulent events in time and space contrasts with the highly structured nature of bedforms (e.g. Liu 1957). Furthermore, turbulence-based theories do not satisfactorily explain the observed scaling of the sand waves initially formed on the bed principally with sediment size rather than flow characteristics (e.g. Coleman and Melville 1996).

The view that ripples and dunes can form only in turbulent flow is attributed by Yalin (1972) primarily to the experimental work of Tison (1949), who carried out a series of experiments to determine whether ripplemarks can be generated in uniform laminar flow. Yalin comments, however, that the experiments of Tison (1949) cannot be regarded as exhaustive. Johnson (1916) also notes the work of de Candolle (1883), who produced ripple marks artificially by experimenting, not only with sand and various substances in powdered form covered by water, but also with liquids of varying viscosity, covered with water and other liquids. De Candolle (1883) was able to make ripples in sand with a variety of fluids, but with olive oil it was found to be impossible (Darwin 1883).

In order to test whether bedform-generation is driven by flow turbulence, it was decided to investigate whether bedforms could be generated for laminar flows over planar sediment beds. To achieve this goal, a glass-walled tilting viscous-fluid channel was constructed measuring 0.3 m $\times$ 0.1 m (wide) $\times$ 2.55 m (long) with a header tank at the inlet and a collection bay at the outlet (Fig. 1a). The centrifugal pump circulating the flow was controlled using a variable speed drive, with vertical sluice gates installed at the upstream and downstream ends of the channel to aid control of flow within the flume (Coleman et al. 1998; Coleman and Eling 2000). A recess in the wooden channel base measuring 0.025 m $\times$ 0.1 m (wide) $\times$ 1.3 m (long) was filled with sediment to create an erodible bed section. Sediment was not recirculated. The fluid used in the experiments was Shell Tellus Grade 32 hydraulic oil, with the bed comprised of respective uniform sediments of median sizes $d = 0.28$–1.6 mm. For the temperature range of the experiments, the fluid density could be taken to be essentially constant at $\rho = 870$ kg/m^3. The kinematic viscosity, ν, of the oil was available in chart form as a function of temperature, with $\nu = 0.8$–1×10^{-4} m^2/s for the experiments undertaken. The particular challenge in the experiments lay in ensuring that the flows would entrain and move the sediments whilst retaining a laminar nature.

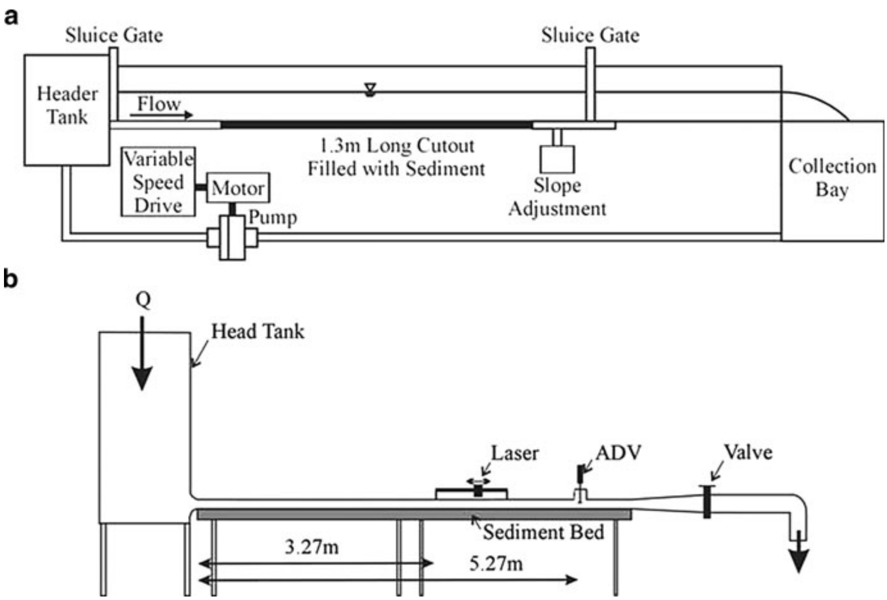

Fig. 1 Schematic drawings of experimental facilities: (**a**) viscous-fluid flume (after Coleman and Eling 2000) and (**b**) water tunnel (after Coleman et al. 2003)

At the start of a bed development run, the bed was smoothed, the settings for the desired flow were established, and then the flow was initiated. For the first runs, bedforms were simply observed. For the later runs, the flow was halted at selected stages of bed development and the centreline bed profile was measured with the channel remaining filled with oil. The bed profiles were measured using a bed-profile measurement system utilising an ultrasonic depthsounder (Coleman 1997), this system being configured to record bed elevation measurements to within ±0.4 mm every 1.2 mm along the flume. The centreline velocity profile midway along the test section was measured using a laser Doppler velocimeter for each run of measured bed profiles.

The results of the tests undertaken indicate that both antidunes and also the seed waves leading to dunes and ripples (Fig. 2) can be generated from plane-bed conditions in open-channel laminar flow, the lengths, shapes, and patterns of generation and growth (Fig. 3) for these sand waves in laminar flows being consistent with observations for alluvial flows (Coleman and Melville 1994; Coleman et al. 1998; Coleman and Eling 2000). In particular, the seed waves are of a preferred wavelength that is relatively insensitive to the characteristics of the applied flow and primarily a function of the size of the sediment. Coleman and Eling (2000) propose that these seed-wave lengths λ for alluvial and laminar open-channel flows over beds of quartz and lightweight sediments of size $d = 0.2$ to $d = 1.6$ mm can be simply described by $\lambda = 175d^{0.75}$, where λ and d are expressed in millimetres. With both ripples and dunes being postulated to subsequently develop from seed